The Royal Aeronautical Society

(FOUNDED 1866)

with which is incorporated The Institution of Aeronautical Engineers

No. 257. MAY, 1932. Vol. XXXVI.

PROCEEDINGS

SIXTH MEETING, FIRST HALF, 67TH SESSION

The Sixth Meeting of the first half of the 67th Session of the Royal Aeronautical Society was held on Thursday, December 3rd, 1931, at 6.30 p.m., in the Lecture Hall of the Royal Society of Arts, 18, John Street, Adelphi, W.C.2., when a lecture entitled "Wheel Brakes and Undercarriages" was delivered by Mr. S. Scott-Hall, M.Sc., D.I.C., A.F.R.Ae.S. Colonel the Master of Sempill, Past President of the Society, was in the chair.

The CHAIRMAN: He had been asked by the President, Mr. Fairey, to apologise for his unavoidable absence and to read the following cable that he had sent to Squadron-Leader Hinkler: "The Council and all Members of the Royal Aeronautical Society wish to congratulate you most heartily on the latest of your many remarkable achievements, that of flying the Atlantic for the first time in a light aeroplane. By your courageous and technically well-planned flights during the past few years you have done as much as anyone to uphold the cause of British Aviation." The Chairman thought they would all agree that this was one of the most remarkable flights that had ever been made. Members who desired to be present on the occasion of the official welcome of Squadron-Leader Hinkler on his landing at the London Airpark at two o'clock on the following Saturday afternoon, could obtain tickets from the Secretary.

Mr. Scott-Hall was an Assistant Technical Officer at Martlesham, where he was engaged in the performance testing of new types of aircraft. He was an Associate Member of the Society and a Busk Memorial Student; in 1925-26 he conducted research on aeroplane stability under Professor Bairstow, in London, and from 1927 to 1929 he worked on aerodynamics at the R.A.E., Farnborough, and carried out full-scale research on low-speed flying. In the latter year he was posted to his present station. Mr. Scott-Hall, therefore, came to them with a fund of useful knowledge on the all-important question which was the subject of his lecture. He had the distinction of being a member of that very exclusive Club, the Caterpillar. The Society had published Mr. Scott-Hall's papers on "Stalled Flying," "The Use of Aircraft for Polar Exploration" (Pilcher Memorial Prize), and "The Spinning of Aeroplanes"; the latter paper was read before the Yeovil Branch.

WHEEL BRAKES AND UNDERCARRIAGES

BY

S. SCOTT-HALL, M.Sc., D.I.C., A.F.R.Ae.S.

Introductory

Until recently an aeroplane undercarriage has generally been called upon to serve two purposes only :—

To absorb the energy due to the vertical velocity of the aircraft when landing ;

To enable the aircraft to be flown off from, and manœuvred over, ground which may be very rough or very soft.

To these requirements are now added a third :—

To absorb the energy due to the horizontal velocity of the aircraft by means of wheel brakes.

These three duties must be carried out with the minimum possible weight and head resistance, for the undercarriage must be as self-effacing in flight as it is all-important on the ground.

The problems connected with wheel brakes are very specialised in themselves and have a particular interest at the present time. For this reason it was decided to deal with them first, and later to turn to the more general aspects of undercarriage development.

Wheel Brakes

Spasmodic attempts have been made to equip aircraft with wheel brakes for some time past. During the war a Fairey Fighter had them fitted, with provision also against nosing over, in the shape of additional wheels placed well forward of the main chassis. In 1923 Vickers fitted a type of band brake to the wheels of a Vimy. These tended to run hot and only decreased the landing run some 20 per cent. They were applied by oil pressure from a pump situated in the cockpit and operated by the pilot.

It is only, however, within the last year or so that the problem has been tackled seriously.

Wheel brakes on aircraft must serve two separate functions if they are to justify their existence.

1. To shorten the landing run.
2. To aid turning on the ground.

The second requirement is not quite so important in the case of the multi-engined aircraft where outboard engines may be used for the purpose, but on single engined machines provision to meet it should certainly be made.

The use of brakes for reducing the landing run of large heavily loaded commercial machines is too obvious to require amplification, and the better and better streamlining and aerodynamic efficiency become, so the need becomes greater and greater.

There is one class of fighting aircraft where their use for manœuvring is especially important and that is in deck-landing types.

The main difficulty in making a successful landing in this case is in keeping the aircraft on a perfectly straight course when the machine is running along the deck and the rudder has become inoperative, due to loss of flying speed. Here efficient, quick reacting brakes are invaluable.

The problems facing the designer at the present time who wishes to equip an existing aircraft with wheel brakes are as follows :—

1. What alterations are necessary to the undercarriage?
2. What method of operation is to be employed by the pilot?
3. How is the pilot's effort to be transmitted or relayed to the brakes?
4. What type of brake is to be used?

The first problem may really be sub-divided into :—

(*a*) The position of the undercarriage.
(*b*) The provision of means for taking the brake torque.

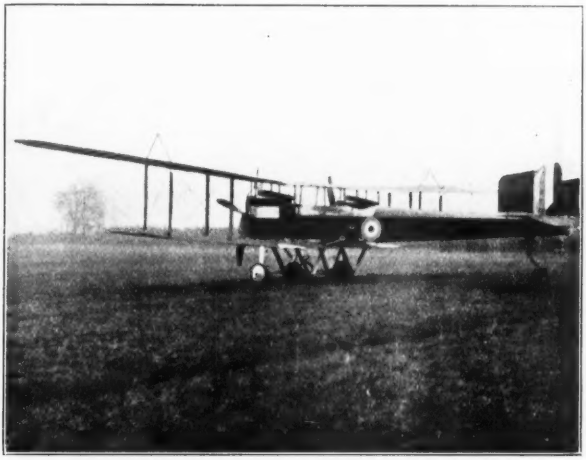


FIG. 1.

Fairey Fighter fitted with wheel brakes and four-wheeled tandem undercarriage (May, 1917).

The Position of the Undercarriage

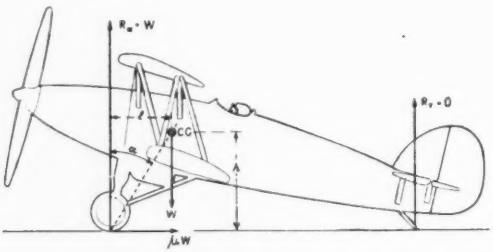
It is obvious that application of brakes to the wheels of an aircraft will produce a moment tending to overturn the aircraft on to its nose. It was the fear of this moment which delayed the installation of brakes for so long and which has produced complicated automatic schemes to release the brakes when the tail starts to rise.

This fear is still considerable and has led in some cases to undercarriages being placed so far forward that tail loads have become excessive, resulting in the well-known troubles of taxying in this condition and difficulty in taking off.

The theoretical case for investigating the tendency to nose over is usually taken as that of an aircraft making a three-point landing with the wheels locked, the ground reaction at the tail being assumed to be zero. The fact that the aircraft is partially airborne under these conditions is ignored and the aerodynamic moments due to wings and tail unit are neglected.

Consideration of this case leads to a criterion for the angle α between the vertical and a line joining the point of ground contact of the wheels to the centre of gravity of the aircraft (see Fig. 2).

The criterion is that for immunity from over-turning this angle must not be less than $\tan^{-1}\mu$ where μ is the coefficient of friction between the tyres and the ground.

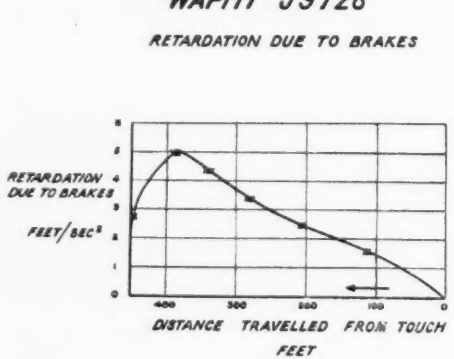


μ = COEFFICIENT OF FRICTION BETWEEN TYRE AND GROUND
OVERTURNING MOMENT = We
RIGHTING MOMENT = μWe
α FOR EQUILIBRIUM $\tan\alpha = \mu$

FIG. 2.

Determination of the position of the undercarriage to give immunity from overturning on the ground.

Measurements of the coefficient of ground friction have been made at Farnborough aerodrome.[1] A mean of the results obtained from nine landings gives a value for μ of 0.3. The highest value obtained was 0.40. The values of the angle α corresponding to these values of μ are 17° and 22° respectively.



R & M 1406 TAKE OFF and LANDING OF AIRCRAFT D ROLINSON M Eng

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FIG. 3.

Variation of the retardation due to brakes during the landing run of a Wapiti aircraft.

[1] "Measurement of Landing Loads." E. T. Jones. R. & M. 1246.

It has been found that if an aircraft has any tendency to overturn it will occur not at the instant of touching nor during the initial part of the run, but later when the speed has fallen to some 20 m.p.h. It is the experience of test pilots that three-point landings may be made in safety with the wheels locked, but that the brake pressure must be released as the landing run proceeds, and this indeed is found to be the most efficient way of using them for pulling up. The reasons for this are that at the instant of touching and during the first part of the run an aircraft is largely airborne, the wheels merely skid, and the pilot is providing an appreciable moment with his elevators, tending to hold the tail down.

Towards the end of the run the aircraft is no longer airborne, with the consequence that the braking effect is much greater, and aerodynamic moments have disappeared (see Fig. 3).

As a result of brake tests of a number of aircraft it has been found that there is no undue tendency to overturn if the critical angle α is 20° or above, but anything less than this may lead to trouble.

The case of the brakes being locked for a tail up landing has not been considered, since if attempts are made to provide against misuse of this kind the resulting position of the undercarriage will lead to very heavy tail loads and difficulty in taking off.

The height of the centre of gravity of the aircraft is obviously a very important factor in the problem. The less it is the better.

The Four-wheeled Undercarriage

For very large aircraft where brakes are being used there is one type of four-wheeled undercarriage which has some interesting features. This has two units, each of which consists of two wheels in tandem mounted at either end of a narrow carriage. The shock absorber leg is pivoted to the central point of the carriage which is further positioned by a system of " N " struts triangulating the structure laterally and fore and aft.

Apart from the obvious advantages of reduction of tyre loading and wider distribution of brake torque for a comparatively small increase in head resistance, there is increased immunity from turning over. The carriage can be shown to

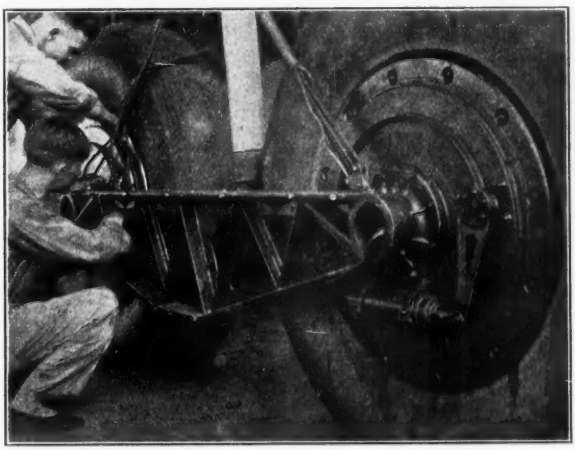

FIG. 4.

Four-wheeled tandem undercarriage on the Junkers G-38 commercial monoplane.

be extremely stable, whilst the aircraft itself instead of tending to rotate about the point of contact between tyre and ground, now rotates about the point of attachment of the oleo strut to the wheel carriage. For a given position of the centre of gravity this results in an increase of the critical angle α, and consequent decrease in the tendency to overturn.

Alterations in attitude of the aircraft whilst the wheels are still in contact with the ground produces a skewing action of the wheel carriage, and it is necessary in the design to allow for side loads on the wheels of considerable magnitude.

The Junkers G.38 is equipped with an undercarriage of this type. This is shown in Fig. 4.

Brake Torque Reaction

When brakes were first fitted to existing undercarriages it was necessary to insert additional members to take the brake torque reaction. These usually took the form of tension members running from the anchorage of the radius rod to the rim of the brake backing plate (see Fig. 5).

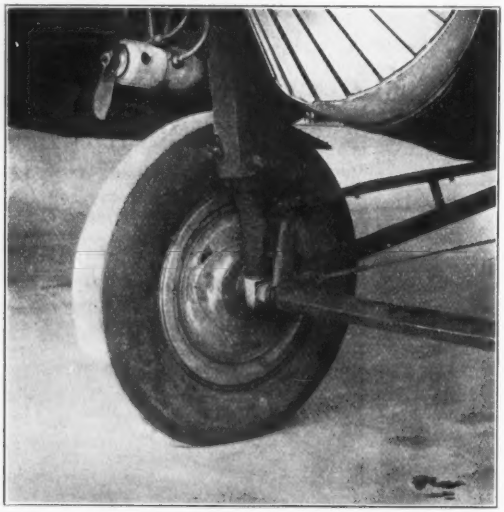

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FIG. 5.

Tension members taking the brake torque reaction on a Vickers Virginia.

With the incorporation of brakes in the initial designs better schemes were provided. One of the most popular is to strengthen the radius rod itself and attach it to the backing plate in such a way that it takes the torque in bending. A further refinement of this is to offset the point of attachment of the oleo leg so that the weight moment so produced helps to balance the brake moment. In this case the radius rod is under bending load when the brakes are off.

It is obviously very important that the oleo leg itself shall be free of any bending, and it is usually fitted with universal joints at either end to ensure this.

A more elaborate scheme which has been adopted in at least one case is to abandon the Vee chassis for a more complicated quadrilateral type in which the short side members take the torque (see Fig. 6). This undercarriage is certainly

very sturdy, and the track has been increased, but the additional structural weight involved by the method is some 35 per cent. of the weight of the original unbraked chassis, and the cost in drag must be considerable also.

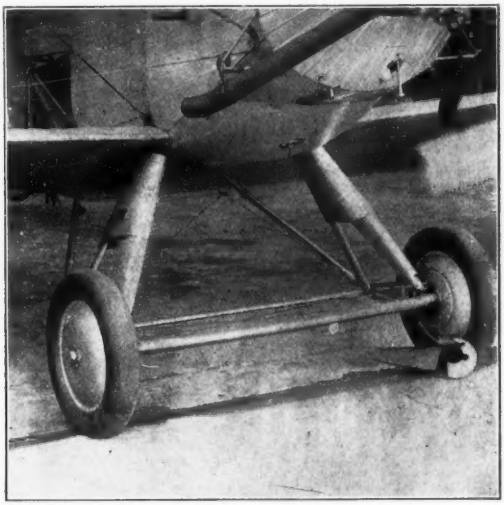

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FIG. 6.

Quadrilateral type undercarriage with wheel brakes.

Method of Operation of Brakes

This is, perhaps, the most vexed question of any at the present time. The pilot when landing has much to occupy his attention, and the first essential of brake operation is that his movements should be easy and instinctive.

During the operations of landing and manœuvring on the ground, a pilot's hands are employed with the control column and throttle respectively.

For large civil aircraft it is not essential that one hand should be actually on the throttle the whole time, and thus here a hand-brake control is possible.

Two classes of military operation, however, demand the freedom of both hands. These are:—

(*a*) Landing and taxying in formation.
(*b*) Deck landing.

In these, one hand is required continuously on the throttle and the other on the stick. The feet are engaged with the rudder. How, then, is the unfortunate pilot going to work anything more with easy instinctive movements?

Hand Control for Civil Aircraft

Where manœuvring in formation and deck landing have not to be considered, a separate hand control is usually adopted. This consists of a lever placed adjacent to the throttle control. Backward movement of the lever applies both brakes together, and differential application is produced by sideways movement or a twist. In hydraulic and pneumatic systems these movements operate suitable pistons or valves (see Fig. 7).

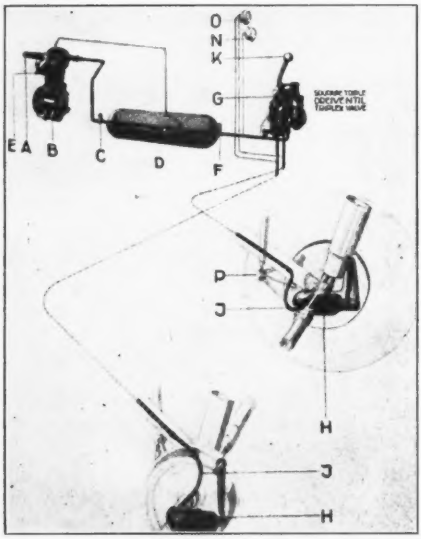

FIG. 7.

Knorr hand-operated pneumatic brake for civil aircraft.

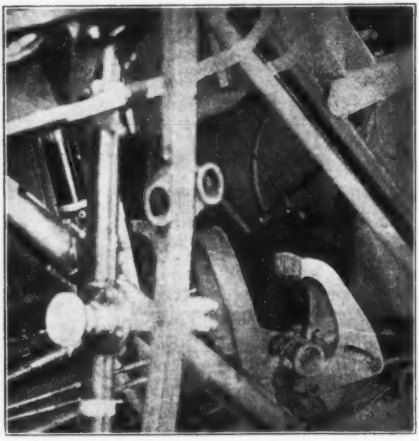

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FIG. 8.

Toe pedal operation of brake on a single-seater fighter.

Methods of Foot Control for Military Aircraft

The most popular of all these is the provision of toe pedals on the rudder bar, which, when depressed, apply the brake on the appropriate side. This scheme certainly meets military requirements better than any others which have been tried. It is quite satisfactory, except where the rudder bar has a large travel, for then the pilot's feet are awkwardly placed for differential operation when the rudder is hard over. For this reason, indeed, some prefer to keep the rudder bar central and steer with the brakes alone.

With toe pedals fitted, the need for a rudder bar adjustable in the air is keenly felt, not only to provide for pilots of varying stature, but also because the best position for applying brakes is not usually the most comfortable one for flying over prolonged periods (see Fig. 8).

Heel control of the same type has been tried, but the movements are awkward and the heels are not so sensitive for judging progressive pressure as the toes (see Fig. 9).

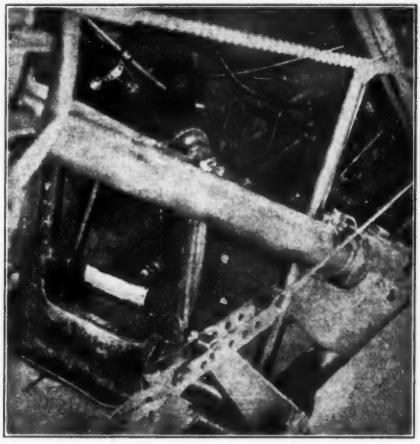

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FIG. 9.

Heel pedal operation of brakes on a two-seater military aircraft. The rudder itself is controlled by pedals instead of the usual rudder bar, and the brake pedals lie inside these.

In both these schemes if a parking brake is required a hand lever with ratchet must be fitted.

A method which does away with any toe or heel movements at the expense of but little extra complication is due to Mr. H. L. Stevens. A double rudder bar is fitted. The rear bar, on which rest the pilot's feet, is capable of movement forward towards the front bar against springs when pressure is applied at both ends. When the rudder bar is central this operates both brakes together. If the rudder is now put over, the brakes are applied differentially in the same sense as the action of the aerodynamic control (see Fig. 10).

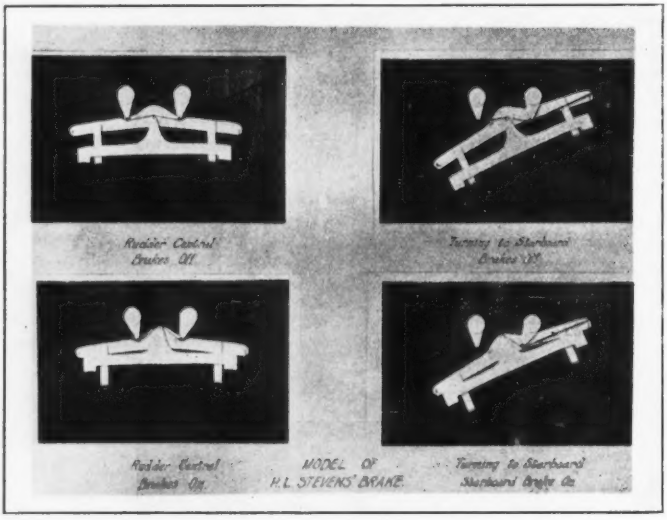

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FIG. 10.

H. L. Stevens' double rudder bar method of brake control.

Combined Hand and Foot Control

Occasional attempts have been made to couple up the braking with the control column so that when the stick is pulled hard back the brakes are applied. A differential control is supplied by the normal rudder movement. This system is not considered good, and is thought to have been largely responsible for one air-

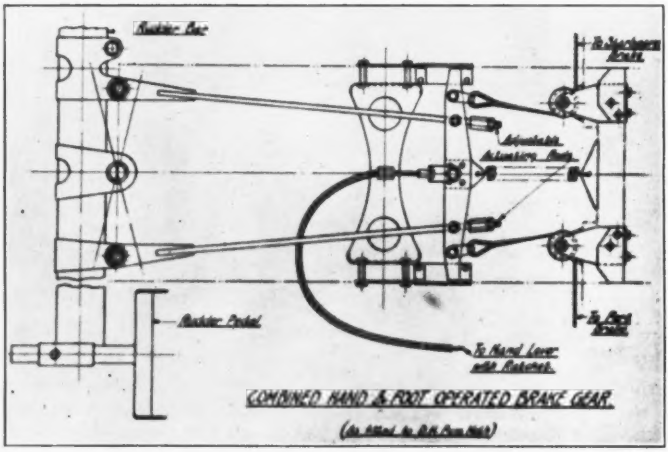

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FIG. 11.

Combined hand and foot brake control.

craft overturning. Supposing that just after contact with the ground the tail hits an excrescence and starts to rise, the elevators must be kept hard up to correct it. At the same time the brakes should be released, and it is impossible to do both with this arrangement.

Another method is to apply both brakes together by a hand lever fitted with a ratchet and working in conjunction with the rudder bar, which then provides differential control (see Fig. 11).

A very interesting combined hand and foot control which allows the pilot to keep one hand on the throttle during the whole period of landing and taxying is due to the Knorr Brake Company of Berlin. The brakes are operated initially

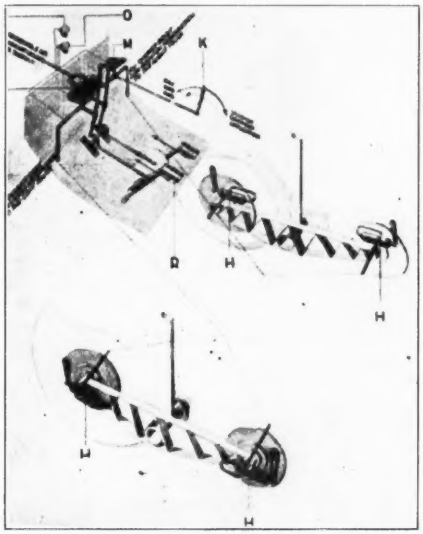

FIG. 12.

Combined throttle lever and rudder pedal brake control as fitted to Junkers G.38 by the Knorr Brake Co., Berlin.

by the throttle lever, which, being in the closed position as far as the engine is concerned, can still be moved, through a gate into a further backward travel on which the brakes are operated together. This same backward movement of the throttle lever brings the rudder bar into operation for differential braking. The advantage of this arrangement in ensuring that the throttle cannot be opened up accidentally when the brakes are hard on is obvious, but, at the same time, running up engines on the brakes cannot be carried out, and chocks must always be used, which is a serious handicap (see Fig. 12).

Pneumatic transmission is used with these brakes in common with most German systems.

Automatic Controls

As a result of the fear of overturning when landing with brakes, a number of automatic devices intended to guard against this danger have been patented.

One method is to arrange that the braking effort shall be directly proportional to the load on the tailskid, and that when the skid leaves the ground the brakes

are released altogether. This is quite easy to incorporate where a hydraulic system is employed to operate the brakes, and was used on the Beardmore " Inflexible."

The Bambridge automatic control also depends for its operation on the attitude of the aeroplane. The wheel axles are mounted in sloping slots. When the tail is on the ground the axles are at the forward and upper end of these slots, but if the aircraft is raised to normal flying attitude the wheels travel aft and downwards. This movement is arranged to release the brakes, which are on so long as the wheels are taking the normal static load and the tailskid is on the ground. They are also released when the aircraft accelerates on taking off (Figs. 13 and 14).

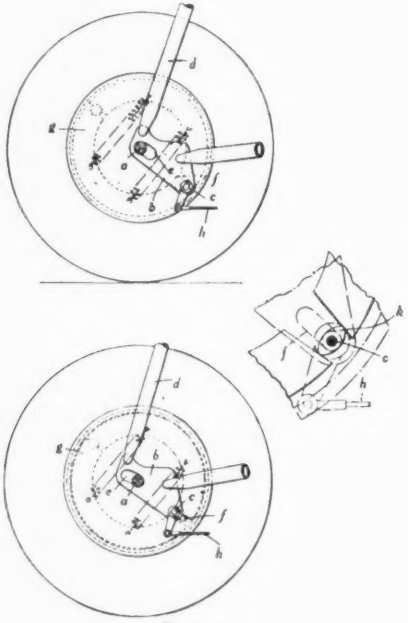

FIG. 13.

Bambridge automatic brake control, showing the pilot's over-riding release.

They are only partially on when the aircraft makes a three-point landing, but gradually-increasing pressure is applied as the landing run proceeds.

The pilot's control consists of an over-riding mechanism to release the brakes for taxying.

Systems of Transmission

This question is almost as controversial as the last. The three methods with which experience has been gained so far are:—

(1) Cable (Bowden or plain).
(2) Hydraulic.
(3) Pneumatic.

Cable transmission has severe disadvantages. It can only be used with the mechanical type of brake. Cable systems have been found in service to require continual adjustment for stretch, and this has sometimes been found necessary

even after only a few landings. Very heavy loads have to be transmitted through the cables, and this continual stretching seems almost inevitable.

The advantages of cable transmission are that it is positive in action, there is no trouble about parking, and, coupled with a mechanical brake, it gives a system which has excellent "feel." Hydraulic transmission with oil as the working fluid is not quite so reliable in action. A parking brake involves difficulties and would mean the provision of some pressure storage device in the system incurring extra weight.

The "feel," with this transmission is not quite so good as would be supposed. This is surprising, since the pressure applied by the pilot at one end of the system is directly proportional to that applied to the brake at the other.

The sweeping advantage of the hydraulic method lies in the fact that adjustments are very rarely needed, any losses in the system being at once made good automatically. Moreover, it is possible to give automatic compensation of the brakes on either wheel.

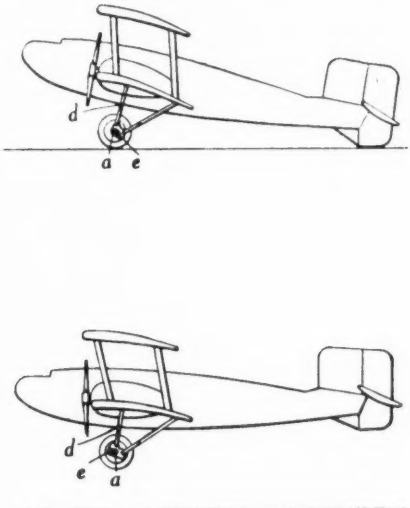

FIG. 14.

Action of the Bambridge automatic brake control.

The actual brake used may be of the mechanical shoe, or the Palmer expanding type, whichever is preferred.

The pneumatic method suffers from the same disadvantages as the hydraulic, but in a worse degree. There is no "feel," since here the pilot is merely opening a valve to apply the brakes. It is more difficult to trace any leakages, and, as fitted at present, a storage vessel for compressed air is required which needs constant recharging, with the risk that if this is overlooked the brakes may be rendered useless. This last criticism is likely to be obviated in the future, for there will be sufficient need for air to justify the fitting of a compressor, and, indeed, this has been done already on one or two large German aircraft.

The advantages are the same as for the hydraulic system.

Examination of these three seems to indicate that the hydraulic or pneumatic methods will be the most popular in the future, with a slight balance in favour of the latter.

Types of Brake

There are a number of widely-differing types of wheel brake in use on aircraft at the present day. Some of these are adaptations of brakes originally designed for automobile work, whilst others have been evolved from the start to meet aircraft problems. All of them, with one exception, are designed for disc or spoked wheels, fitted with high pressure tyres, where there is plenty of room to accommodate the brake gear within the wheel itself. They are of the following types:—

(*a*) Internally expanding independent shoe.
(*b*) Servo shoe.
(*c*) Expanding tube.
(*d*) Multiple disc.

The exception is the sleeve type brake designed for use with low pressure air wheels.

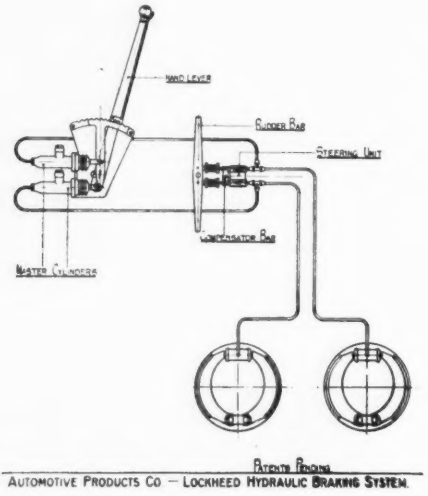

FIG. 15.

Diagrammatic layout of Lockheed combined hand and foot controlled brake. The brakes are of the independent two-shoe type and are oil operated.

The Internally Expanding Shoe Brake

The simplest type of expanding shoe brake is the one which has been used for so long in motor car practice, consisting of two separately anchored shoes.

(1) *The Lockheed Hydraulic Brake* is of the independent shoe type expanded by horizontally opposed pistons. Fig. 15 gives a diagrammic lay-out of a combined hand and foot control. The brakes are applied initially by a hand lever operating pistons, in two master cylinders, one for each wheel. The pressure in these cylinders is automatically equalised as the lever is applied. Two further cylinders in the system are operated by the rudder bar and provide differential control. A compensating bar is fitted across the pistons of the rudder cylinders to ensure that with equal pressures on each wheel their available travel for differential braking shall be equal. If any loss of oil occurs in the system a

vacuum is created in the master cylinders when the brakes are released and fresh oil is drawn from a small reservoir (not shown in the diagram). The Lockheed systems are tested initially up to pressure of 2,000lb. per sq. inch, and the working pressure lies between 750 and 850lb. per sq. inch.

(2) *The Vickers self-energising brake* also makes use of two independent shoes, the hydraulic pressure used to operate them being raised by means of the rotation of the landing wheel itself, thus relieving the pilot of any effort save that of operating a valve. Inside the wheel is a pump which is driven by a cam. This pump supplies a storage bottle which is one-third filled with oil, the remaining upper part containing air. In taking off, the pump raises the pressure in the system to the normal working value of 1,200lb. per sq. inch. This pressure is maintained for considerable periods and the brakes are available for use when landing again. Should the pressure have fallen for any reason, it can be raised prior to landing by means of an emergency hand pump. A relief valve prevents excessive pressures being generated in the system, and a parking brake operated mechanically is also provided.

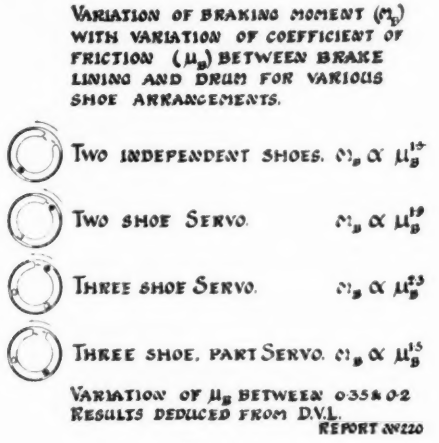
VARIATION OF BRAKING MOMENT (M_D) WITH VARIATION OF COEFFICIENT OF FRICTION (μ_B) BETWEEN BRAKE LINING AND DRUM FOR VARIOUS SHOE ARRANGEMENTS.
TWO INDEPENDENT SHOES. $M_D \propto \mu_B^{1.0}$
TWO SHOE SERVO. $M_D \propto \mu_B^{1.9}$
THREE SHOE SERVO. $M_D \propto \mu_B^{2.3}$
THREE SHOE, PART SERVO. $M_D \propto \mu_B^{1.5}$
VARIATION OF μ_B BETWEEN 0·35 & 0·2
RESULTS DEDUCED FROM D.V.L. REPORT No.220

FIG. 16.

Variation of braking moment with variation of friction coefficient between brake lining and brake drum.

The Servo Shoe Brake

A well-known and important development of the independent two-shoe brake is the Servo brake, in which the frictional load on the primary shoe is used to apply the secondary shoe. The advantage claimed for this system is a much greater brake torque for the same exertion on the part of the pilot, and with no increase in load in the transmission gear. Some designers dislike the idea of using a Servo brake because of the possible danger of seizure occurring if the shoes become badly worn. Again, the brake drum must be perfectly concentric with the axle and backing plate for efficiency, and this leaves no margin for wear on the axle itself, and roller or ball bearings must be fitted.

The number of shoes may be increased to three, but troubles then arise, due to uneven wear, and this type has been found to be generally unreliable.

One of the greatest troubles with brakes is the result of oil getting on to the linings. The coefficient of friction between the brake lining and the drum may fall from its normal value of 0.35, to, say, 0.2, under these conditions.

The variation of brake torque for a given variation of this coefficient is very much greater in the two-shoe Servo brake than it is in the independent two-shoe, and becomes greater and greater as the number of floating shoes is increased.

Fig. 16 gives the results of calculations of the variation of braking moment (M_B) with variation of coefficient of friction (μ_B) between brake lining and drum for various shoe arrangements. The results are deduced from curves given in D.V.L. Report No. 220, " Experiments with Landing Wheel Brakes," by Franz Michael.

The curves referred to show the variation of braking moment with variation of (μ_B), the braking moment for (μ_B)=0.3 being taken as 100 per cent. and corresponding to the normal braking moment for which the brake is to be measured.

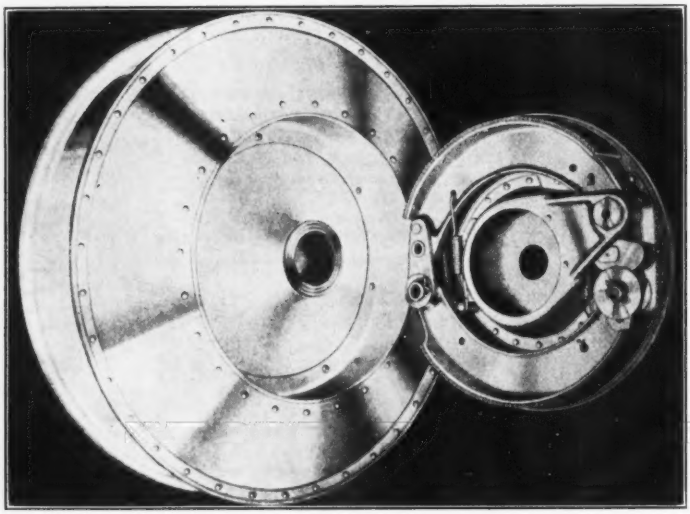

FIG. 17.
Bendix-Perrot two-shoe Servo brake.

The variation of (μ_B) is restricted to the range 0.35 to 0.2 for the present purposes and a value for the index (n) found in the equation $M_B = k \cdot \mu_B^n$ for each of the brake shoe arrangements.

This index gives a direct measure of the unreliability of any one of the arrangements investigated under working conditions when the value of (μ_B) will vary due to the presence of oil, water, or grit. The results show that the three-shoe servo is the least reliable, whilst the independent two-shoe lies at the other end of the scale. They also show that the three-shoe part servo is slightly more reliable than the two-shoe servo, this appearing as a consequence of the negative servo effect of the third independent shoe.

It will be realised, of course, that this method of analysis is only approximate. The brake moment due to any given brake shoe arrangement is more accurately given by

$$M_B = A\mu_B + B\mu_B^2 + C\mu_B^3 + \ldots X\mu_B^n$$

where n=the number of servo shoes.

The values of the constants A, B, C, etc., are determined by the geometry and sizes of the different shoes.

The action, then, of a Servo brake is likely to be affected to a greater extent by the presence of oil than one of the independent type, and if the number of shoes is increased to more than two, the service of the brakes will probably be extremely erratic. This has been experienced in practice.

(1) *The Bendix-Perrot* two-shoe Servo brake is a development of the well-known automatic brake produced by the same company (see Fig. 17).

The brake is designed to be operated by mechanical transmission, and in order to overcome the difficulties of cable stretch previously referred to, a long cam operating lever has been incorporated in the latest unit, to reduce the load in the transmission. This lever is arranged inside the brake drum, so that the drag in flight is not increased. The whole brake itself is enclosed within the wheel.

(2) *The Vickers Hydraulic Brake* has a two-shoe Servo unit, with a third independent shoe (see Fig. 18). This was evolved with a view to relieving the

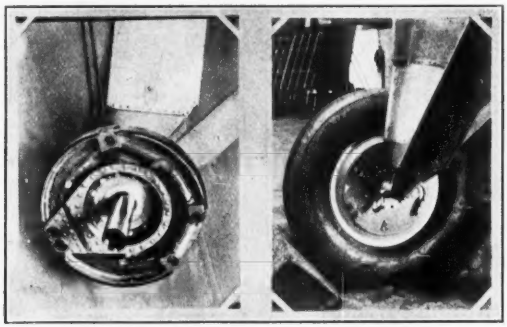

FIG. 18.

Vickers hydraulic brake. This is a two-shoe Servo unit with a third independent shoe.

pilot of some of the exertion required in brake operation on large multi-engined aircraft. It is being superseded, however, by the less complicated two-shoe type. The pilot is provided with a hand pump, and the pressure is applied to the mechanical unit via the usual hydraulic cylinder. The first stroke of the pump backwards from the neutral position raises the pressure of the oil in the system to some 200lb. per sq. inch, taking up any slack and applying the brakes lightly. This initial pressure can be maintained without further action on the part of the pilot until the pump lever is forced hard forward from neutral, thus operating the release valve. Just before landing, then, this initial pressure is created. Further working strokes with the pump raise the pressure to 1,000lb. per sq. inch, but to maintain this the pilot must hold the lever back by hand. The object of the design is to enable him to " feel " his brakes easily.

A steering valve can be incorporated, and differential control obtained from the rudder bar. When the rudder bar is pushed hard over, the pressure on the appropriate wheel is allowed to fall to the initial 200lb. per sq. inch. On centralisation of the rudder, the brake pressures are equalised once more. An oil reservoir is fitted to the pump from which the system is kept continually charged.

All these mechanical brake units so far described are arranged to be entirely contained within disc wheels, so that no additional drag in flight is incurred.

Expanding Sleeve Brake

There is one type of wheel in use in which the diameter available for installing brake gear is extremely limited. This is the low pressure air-wheel, in which the

tyre is mounted straight on to the hub. Here, however, there is a much greater width available, and advantage has been taken of this for braking purposes (see Fig. 19).

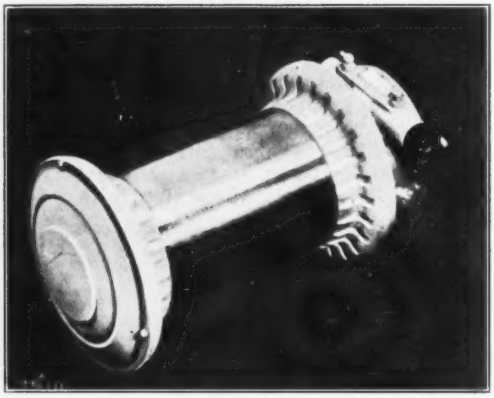

FIG. 19.
Goodyear low pressure air wheel hub, incorporating an expanding sleeve brake.

The Goodyear Brake consists in principle of a small diameter sleeve of brake lining material which can be expanded against the cylindrical brake drum by means of toggles operating as a wedge. The details are shown in Fig. 20. The

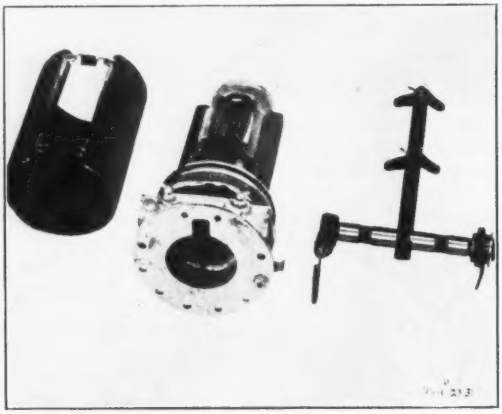

FIG. 20.
Assembly of Goodyear expanding sleeve brake.

unit has been arranged for a cable or rod transmission system, but, of course, could equally well be adopted for operation by hydraulic means. Over-heating troubles have not been experienced with this brake, though they were anticipated.

Overheating

It seems to be tacitly assumed by many that aircraft brakes do not suffer from overheating trouble, owing to the short periods over which they are used. This is not the case, and better provision should be made than at present for dissipating the heat generated.

Multiple Disc Brake

The Sikorsky Company of America, faced with the problem of bringing large aircraft to rest, avoided the self-energising Servo type, on account of the fear of seizure, and produced a multiple disc type instead. This unit consists of two discs of the same diameter as the rim of the wheel, running between stationary discs mounted on the axle. Hydraulic pressure is applied to the stationary discs tending to clamp the rotating members between them. The method provides much better dissipation of heat than other types, at the expense, however, of additional drag (see Fig. 21).

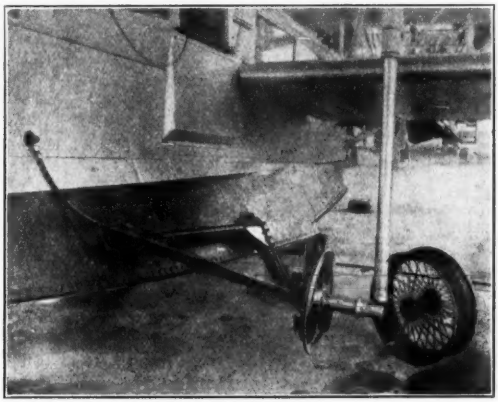

FIG. 21.

Sikorsky multiple disc brake.

Expansion Tube Brake

There is one type of brake which is a radical departure from all those so far described. It can be used with either oil or air operation, is extremely simple and light, does not require accurate concentricity between brake drum and axle, and utilises the whole available area of the brake drum.

The Palmer Brake consists of a circular expansion tube of specially prepared rubber housed in a channel within the periphery of the drum. To the whole of the outer circumference of this tube are attached castellated friction blocks. The castellations fit into corresponding slots in the channel, which is attached to the backing plate, and so transmit the brake torque when pressure is applied to the expansion tube (see Fig. 22).

For hydraulic operation a special oil is used (a mixture of glycerine and methylated alcohol) which is claimed to have no deteriorating effect on the material of the expansion tube.

When pneumatic operation is used, it is necessary at present to carry a compressed air cylinder of which the normal working pressure is 1001b. per sq. inch.

The pressure is applied to the brakes through the medium of a valve operated by the pilot. This valve is designed to give the pilot progressive " feel," on the application stroke and on release cuts off the supply, and exhausts the brake system.

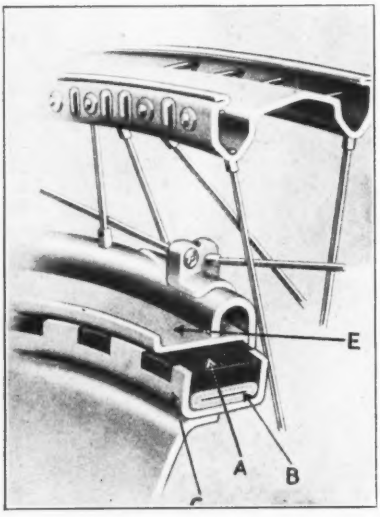

FIG. 22.

Palmer expansion tube brake.

Results of Tests of Brake Systems

Some extensive research has been carried out with Knorr wheel brakes at the D.V.L. Adlershof,[2] in which measurement of deceleration, brake torque and pilot's effort have been made.

In this country extensive handling trials have been carried out with various types of brake and different methods of operation, and a large number of measurements of landing runs with and without these brakes in use have been made.

The results of these tests are shown in Fig. 23, which gives the percentage reduction of landing run due to the use of brakes plotted against weight of aircraft.

The landing run of an aircraft depends on many factors, and it is obvious that the reduction of run effected by the use of brakes will be very much greater on an aircraft on which the other retarding forces are small, than it will be on one where these are large. This applies particularly to machines fitted with tail wheels, as compared with those equipped with skids.

The test results are very scattered, but there is a tendency for the reduction of the landing run to increase with increase of total weight of aircraft. The result of 33 per cent. reduction for the Inflexible landing at an all up weight of 31,000lb. contradicts this, but may be ignored, since the brake scheme on this aeroplane was of very early design.

The high efficiency which can be attained with the three-shoe brake is well illustrated, as also is the popularity of the mechanically-operated two-shoe Servo type for aircraft up to 6,000lb. total weight. Above this weight hydraulic and pneumatic types hold the field.

[2] Franz Michael. " Wheel Brakes." D.V.L. Report No. 220.

Drag and Weight of Brakes

Since all the brakes which have been considered are housed within the wheels, except one, it can be said that there need be little or no additional drag. The additional weight involved is of the order of 1 per cent. of the total weight of the aircraft, and in view of their advantages there are few cases in which this cost is not worth while.

A table giving the detailed weights of various brake systems for aircraft of different all-up flying weights is given on pages 406 and 407.

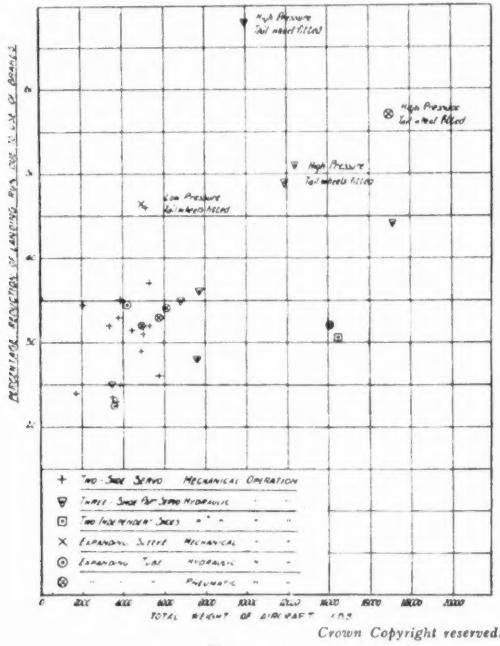
High Pressure Tail wheel fitted
High Pressure Tail wheel fitted
High Pressure Tail wheel fitted
Low Pressure Tail wheel fitted
PERCENTAGE REDUCTION OF LANDING RUN DUE TO USE OF BRAKES
Two-Shoe Servo Mechanical Operation
Three-Shoe Out-Servo Hydraulic
Two Independent Shoes
Expanding Steel Mechanical
Expanding Tube Hydraulic
Pneumatic
TOTAL WEIGHT OF AIRCRAFT

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FIG. 23.

Results of measurements of landing runs with and without brakes on various aircraft.

GENERAL ASPECTS OF UNDERCARRIAGE DEVELOPMENT

Landing and Taxying Loads

Measurements have been made from time to time of the maximum vertical velocities and accelerations likely to be encountered in landing and taxying. One of the most complete investigations carried out was that on a De Havilland 9 aeroplane. Measurements were made of the vertical, longitudinal and lateral loads, and of the vertical and drift velocities for various types of landing.[3] In these experiments the maximum vertical velocity recorded in a purposely severe landing, was 9.3 feet per second, and the maximum acceleration 4.1g. The maximum vertical acceleration while taxying on a rough aerodrome was 3.1g. The undercarriage was a specially designed unit, incorporating close wound helical steel springs for taking the vertical reaction.

[3] "Measurement of Landing Loads." E. T. Jones. R. & M. 1246.

TABLE I.—WEIGHTS

(For Two-Wheel Chassis with Provision

Flying Weight of Aircraft. lbs.	LOCKHEED. Hydraulic (Oil) Operation. Two Independent Shoes.	BENDIX-PERROT. Mechanical Operation. Two Shoe Servo.	GOODYEAR. Mechanical Operation. Expanding Sleeve.
	High Pressure Tyres.	(a) *High Pressure Tyres.*	25×11-4 *Airwheels.*
	10in. Brake.	10in. Brake ... ... 10 lbs.	Brakes* ... ... 13 lbs.
	Total Brake Equipment 19lbs.	Operational Gear ... 6 ,,	Operational Gear ... 6 ,,
		Total Brake Equipment 16 lbs.	Total Brake Equipment 19 lbs.
3,000		(b) *Intermediate Low Pressure Tyres.*	
		7in. Brake ... ... 4½ lbs.	
		Operational Gear ... 6 ,,	
		Total Brake Equipment 10½ lbs.	
	High Pressure Tyres.	(a) *High Pressure Tyres.*	35×15-6 *Airwheels.*
	16in. Brake.	12in. Brake ... ... 12 lbs.	Brakes* ... ... 22½ lbs.
	Total Brake Equipment 35lbs.	Operational Gear ... 9 ,,	Operational Gear ... 9 ,,
		Total Brake Equipment 21 lbs.	Total Brake Equipment 31½ lbs.
6,000		(b) *Intermediate Low Pressure Tyres.*	
		10in. Brake ... ... 7½ lbs.	* By difference of Hub with Brake and Hub without Brake.
		Operational Gear ... 9 ,,	
		Total Brake Equipment 16½ lbs.	
	High Pressure Tyres.	(a) *High Pressure Tyres.*	44×20-8 *Airwheels.*
	24in. Brake.	20in. Brake ... ... 34 lbs.	Brakes† ... ... 55 lbs.
	Total Brake Equipment 65lbs.	Operational Gear ... 12 ,,	Operational Gear ... 12 ,,
		Total Brake Equipment 46 lbs.	Total Brake Equipment 67 lbs.
17,000		(b) *Intermediate Low Pressure Tyres.*	† Estimated.
		14in. Brake ... ... 18 lbs.	
		Operational Gear ... 12 ,,	
		Total Brake Equipment 30 lbs.	

NOTES.

1. Brake sizes above are as quoted by makers for aircraft of weights as specified.
2. The weight of brake drums is not included except in the case of the Goodyear type in which the bore of the hub forms this unit.
3. The additional structural weight of the undercarriage consequent to fitting brakes is not included.

OF BRAKE GEAR.

FOR DIFFERENTIAL OPERATION OF BRAKES.)

PALMER.

Hydraulic (Oil) Operation. Expanding Tube.			Pneumatic Operation. Expanding Tube.		
High Pressure Tyres.			*High Pressure Tyres.*		
12in. Brake.	lbs.	ozs.	12in. Brake.	lbs.	ozs.
Brake Assemblies (2)	3	12	Brake Assemblies (2)	3	12
Foot Cylinders (2) including weight of oil	2	14	Relay Valves (2)	1	7
Reservoir including weight of oil ...		6½	Air Cylinder (678 cu. ins.) ...	6	12
Aluminium Tube (20ft.)		8	Pressure Gauge (1)		4¾
I.R. Hose (5ft.)		5¾	Aluminium Tube (25ft.)		6½
Spring Wire Clips (20)		4	I.R. Hose (5ft.)		1¼
T. Piece (1)		½	Spring Wire Clips (25)		5
			T. Pieces (2)		1
			Inflating Valve (1)		1
Total Brake Equipment	8	2¾	Total Brake Equipment	13	2¼
High Pressure Tyres.			*High Pressure Tyres.*		
13¾in. Brake.	lbs.	ozs.	13¾in. Brake.	lbs.	ozs.
Brake Assemblies (2)	9	2	Brake Assemblies (2)	9	2
Foot Cylinders (2) including weight of oil	2	14	Relay Valves (2)	1	7
Reservoir including weight of oil ...		6½	Air Cylinder (848 cu. ins.) ...	7	15
Aluminium Tube (25ft.)		10	Pressure Gauge (1)		4¾
I.R. Hose (5ft.)		5¾	Aluminium Tube (40ft.)		10
Spring Wire Clips (20)		4	I.R. Hose (5ft.)		1¼
T. Piece (1)		½	Spring Wire Clips (25)		5
			T. Pieces (2)		1
			Inflating Valve (1)		1
Total Brake Equipment	13	10¾	Total Brake Equipment	19	15
High Pressure Tyres.			*High Pressure Tyres.*		
28in. Brake.	lbs.	ozs.	28in. Brake.	lbs.	ozs.
Brake Assemblies (2)	33	0	Brake Assemblies (2)	33	0
Foot Cylinders (2) including weight of oil (Special Gear)	7	0	Relay Valves (2)	1	7
Reservoir including weight of oil ...		6½	Air Cylinder (1272 cu. ins.) ...	11	0
Aluminium Tube (30ft.)		12	Pressure Gauge (1)		4¾
I.R. Hose (5ft.)		5¾	Aluminium Tube (60ft.)		15
Spring Wire Clips (20)		4	I.R. Hose (5ft.)		1¼
T. Piece (1)		½	Spring Wire Clips (25)		5
			T. Pieces (2)		1
			Inflating Valve (1)		1
Total Brake Equipment	41	12¾	Total Brake Equipment	47	3

Weights of brake drums for High Pressure Tyred Wheels (Dunlop) :—

Brake Drum Diameter. inches.	Brake Drum Weight (2 wheels). lbs.
10	9½
12	12
16	15
20	26½
24	30½

TABLE II.

UNDERCARRIAGE FAILURES ON NEW MILITARY TYPES AT MARTLESHAM HEATH.

JUNE, 1929—JUNE, 1931.

Type of Aircraft.	Flying Weight (lbs.)	Landing Speed (m.p.h.)	Type of Undercarriage (when failure has occurred).	Brakes Fitted.	Failures.	Resulting Damage to Aircraft.
1. Single Seaters	2900	50	——	—	Tailskid (fittings).	Very slight to rudder.
(Single Engine)	3260	65	Straight through axle	No	Undercarriage (radius strut).	Slight to wing spars. Undercarriage written off.
	3350	63	——	—	Tailskid (tube in bending).	Nil.
	3450	69	——	—	Tailskid (tube in tension).	Nil.
	3620	65	Straight through axle.	Yes	Undercarriage (axle bent).	Nil.
	3800	62	——	Yes	Tailskid (tube in tension).	Nil.
	3960	62	——	—	Tailskid (shoe worn off).	Nil.
	Total Number of New Types Tested in this Class =22 Number of New Types having Undercarriage Failures=2 Number of New Types having Tailskid Failures =5 Number of New Types having Wheel & Tyre Failures=Nil.					
2. Two Seaters	4300	61	——	—	Tailskid (strut in compression).	Nil.
(Single Engine)	4750	65	Split axle.	Yes	Wheel (disc casting).	Nil.
	4810	63	Straight through axle.	No	Wheels (spokes failing).	Nil.
	5660	59	——	No	Tyres (splitting under excessive load).	Nil.
	6000	65	——	—	Tailskid (tube in torsion).	Fuselage cross member buckled.
	6150	62	——	—	Tailskid (rivets torn).	Bottom longeron damaged.
	5750	67	Split axle.	Yes	Undercarriage (pin sheared on oleo strut).	Considerable damage to wing and tailplane. Half undercarriage written off.
	5750	67	Split axle.	Yes	Tailskid (fuselage cross member failed in bending).	Nil.
	5750	67	Split axle.	Yes	Tailskid (skid tube bent under side load).	Nil.
	Total Number of New Types Tested in this Class =18 Number of New Types having Undercarriage Failures=1 Number of New Types having Tailskid Failures =4 Number of New Types having Wheel & Tyre Failures=3					
3. Multi Engine.	Total Number of New Types Tested in this Class=1 Undercarriage Failures Nil.					

TABLE III.

UNDERCARRIAGE FAILURES ON NEW CIVIL TYPES AT MARTLESHAM HEATH.

JUNE, 1929—JUNE, 1931.

Type of Aircraft.	Flying Weight (lbs.)	Landing Speed (m.p.h.)	Type of Undercarriage (when failure has occurred).	Brakes Fitted.	Failures.	Resulting Damage to Aircraft.
1. Single and Two-Seater Sports and Training	1500	40	Split Axle.	No	Undercarriage (fitting)	Considerable damage to fuselage. Undercarriage written off.
	1740	50	Split Axle.	No	Undercarriage (fittings)	Considerable damage to wings and fuselage.
			Total Number of New Types Tested in this Class =15 Number of New Types having Undercarriage Failures=2 Tailskid and Wheel and Tyre Failures Nil.			
2. Passenger Carrying (Single Engine)	3870	55	Split Axle.	Yes	Undercarriage (shock absorber rubbers failed).	Nil.
	1800	50	Split Axle.	No	Undercarriage (two failures of shock absorber struts).	Nil.
	1800	50	Split Axle.	No	,,	Nil.
			Total Number of New Types Tested in this Class =4 Number of New Types having Undercarriage Failures=2 Tailskid, Wheel and Tyre Failures Nil.			
3. Passenger Carrying (Multi Engine)	5400	50	Split Axle.	No	Undercarriage (pin sheared in oleo leg taking off).	Very slight.
			Total Number of New Types Tested in this Class =8 Number of New Types having Undercarriage Failures=1 Tailskid, Wheel and Tyre Failures Nil.			

Experiments carried out by the N.A.C.A.[4] on landing gears for an F.6 C-4 aeroplane gave maximum results of 3.6g. for a rubber cord gear and 2.3g. for an oleo gear under severe landing conditions. Further experiments were carried out in America[5] on a VE-7 aeroplane with a practically rigid undercarriage and Goodyear Musselman air wheels. At an inflation pressure of 15lb. per sq. inch a maximum acceleration of 4.3g. was recorded—the vertical velocity of the aircraft being 9.4 feet per second, and with an inflation pressure of 5lb. per sq. inch, a maximum of 3.2g., with a vertical velocity of 10.5 feet per second.

The fact brought out in all these experiments is that the taxying loads, especially on a rough aerodrome, are comparable in magnitude with those produced by all but the most severe pancake landings.

It is considered desirable by some that, if any part of an aircraft is going to fail under a very heavy landing, the first part to break should be the undercarriage, because this unit is easier to replace than, say, the longerons or the fuselage. This argument is sound provided that collapse of the undercarriage when the aircraft is still travelling at some speed does not cause overturning with far more serious consequence to the wings. Unfortunately in practice this is what usually happens.

A strong undercarriage capable of absorbing heavy landing shocks may cost something extra in weight and drag, but it will save over and over again in repairs and maintenance and even avert what might otherwise be a write-off.

Tables II and III have been prepared from an analysis of undercarriage failures at Martlesham Heath between June, 1929, and June, 1931. Table I gives the failures which occurred during this period on new military types and Table II those which occurred on the corresponding civil types.

Although several undercarriage failures shown in these tables resulted in no damage to the aircraft, it should be pointed out that the rigid system of inspection in force led to the detection of faults in these cases before collapse of the undercarriage took place.

One of the most striking points brought out is the number of tailskid failures amongst the military types. No doubt the number among the civil aircraft would be equally great, but for the fact that these tests are usually of such short duration, that they do not get sufficient wear and tear whilst undergoing trials to develop trouble of this kind. The tailskid is, without doubt, one of the most unsatisfactory members of the structure of an aeroplane.

An interesting point in connection with shock absorption is, that if the vertical landing velocity and the maximum permissible acceleration are specified and the fact that the aircraft is partially airborne is ignored, then the travel required on any shock absorber is independent of the total weight of the machine. It is this fact that causes the undercarriages of some light aircraft to look so unwieldy in flight when compared with those of their heavier relations, and it also has an important bearing on the attempts which have been made recently to dispense with oleo legs on aircraft to which low-pressure air wheels are fitted.

Oleo Legs

The design of shock-absorbing legs has been dealt with very fully in previous papers[6] and it is not proposed to go into the detail of this problem here.

[4] N.A.C.A. Report 366. "Dynamic and Flight Tests on Rubber-Cord and Oleo-Rubber-Disc Landing Gear for an F.6-C.4 Airplane." W. C. Peck.

[5] N.A.C.A. Report 381. "Static Drop and Flight Tests on Musselman Type Airwheels." W. C. Peck and A. P. Beard.

[6] "Aircraft Undercarriages." J. D. North. Aeronautical Journal, Feb., 1920.—"Oleo Undercarriage Design." G. H. Dowty. Proceedings of Institution of Aeronautical Engineers, Nov., 1922.—"Aircraft Alighting and Arresting Mechanisms." G. H. Dowty. Proceedings of Institution of Aeronautical Engineers, Feb., 1927.

The following very brief descriptions of several modern types of leg are given to illustrate what provision is made for combining the requirements of absorbing landing shock with those of taxying.

Vickers (Fig. 24)

The Vickers oleo-pneumatic leg contains air in an upper fixed cylinder and oil in a lower one which moves upwards inside the first under compression loads. Within the upper cylinder and attached to its head is a tapered tube open at the lower end. The lower cylinder is provided with a piston head with a ring of leak holes near the circumference, and a large central orifice through which the fixed tapered tube passes on the compression stroke. The lower cylinder has a bore only very slightly larger than that of the upper end of the tapered tube so that an annular space is left between the outside of the lower cylinder and the inside of the upper cylinder when the leg is compressed, and it is into this annular space that the piston head leak holes then discharge.

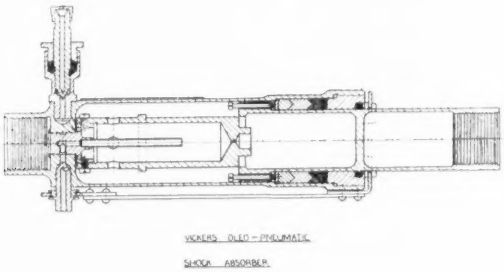

FIG. 24.
Section of Vickers oleo-pneumatic shock absorber.

A non-return plate valve is fitted to these holes so that the return flow of oil is restricted to one orifice only and the rebound is damped.

Moderate shocks are thus dealt with by the outer mechanism and the energy of heavy landings is absorbed by the variable orifice provided by the tapered tube. Springing is provided by the compressed air. Leakage of oil is provided against by the fitting of hydraulic cup washers and packing rings secured by a gland nut.

Boulton & Paul (Figs. 25 and 26)

This leg again provides pneumatic springing for taxying purposes, the air being compressed to an initial pressure of 125lb. per sq. inch with the leg fully extended. A floating diaphragm separates the lower part of the leg containing this air from the upper containing the oil. The oleo piston has a constant orifice leak hole with a relief valve to deal with rapid compression of the leg.

Fairey III.F (Figs. 27 and 28)

This leg, although not incorporating a tapered needle of the type which has been proved so effective as a means of obtaining constant resistance and total absorption of energy, has a variable orifice for the passage of oil on the compression stroke which serves the same purpose.

The orifice area may be easily adjusted for variations of load by means of a small valve placed at the head of the leg. In addition to this variable orifice area, fixed leak holes are provided in the head of the oleo piston. To ensure good taxying qualities a special air bottle is fitted.

The compression of the air in this bottle on the impact stroke ensures that the oil follows the movement of the piston rapidly on rebound. Compression rubbers are fitted on two columns.

The travel of the leg is eight inches.

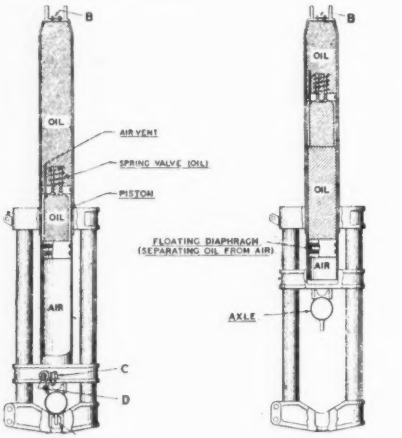

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FIG. 25.

Section of Boulton and Paul oleo leg.

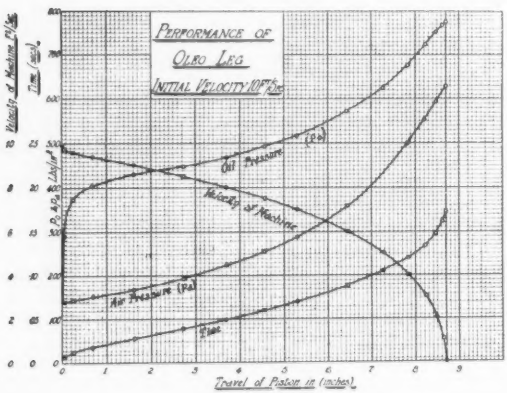

FIG. 26.

Dynamic performance curves for Boulton and Paul oleo leg.

Laboratory Testing of Oleo Legs

Something should be said about modern laboratory methods of testing oleo legs. It is quite evident that when testing an oleo leg only a dynamic drop test gives anything approaching actual flying conditions and that progressive load

tests are useful only for comparative purposes in the case of springing devices, being quite inapplicable to the oleo gear itself.

A considerable amount of work has been carried out at Farnborough on this question of dynamic testing[7] and apparatus is now being installed at the Royal Aircraft Establishment with which tests of oleo legs can be carried out with close simulation of actual landing conditions.

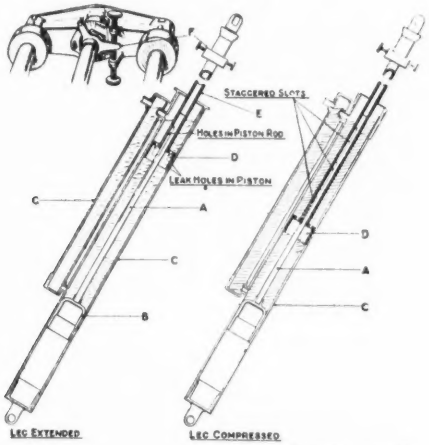

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FIG. 27.
Diagrammatic section of Fairey III-F. oleo leg.

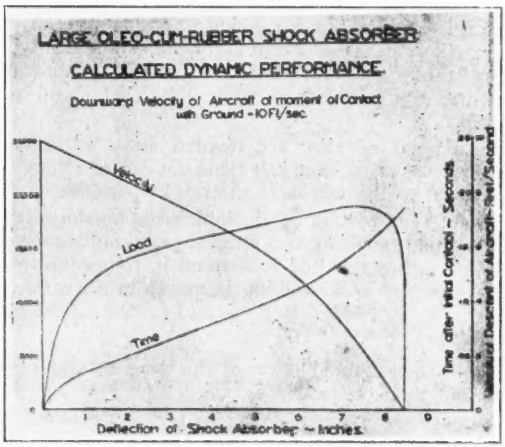
LARGE OLEO-CUM-RUBBER SHOCK ABSORBER
CALCULATED DYNAMIC PERFORMANCE
Downward Velocity of Aircraft at moment of Contact with Ground - 10 Ft/sec.
Velocity
Load
Time
Deflection of Shock Absorber - Inches
Time after Initial Contact - Seconds

FIG. 28.
Dynamic performance curves for Fairey III-F. oleo leg.

[7] " Dynamic Tests of Oleo Struts." T. W. K. Clarke and W. D. Douglas. R.A.E., M.T., 5488.

The load in falling is made to compress air in cylinders during the last portion of the drop, thus allowing for the fact that the aircraft when landing is partially airborne. The elastic effect of tyre and axle and the inertia of the moving parts of the undercarriage are also represented.

Taxying Qualities

A test pilot often levels the criticism against an undercarriage that it is either too harsh or too soft when taxying. There is no doubt that one of the greatest difficulties in the design of shock absorber legs is to provide good taxying qualities, in combination with the capability to absorb the shock of a heavy landing. This question is to a great extent bound up with the amount of damping of the oil which should be restricted under taxying conditions. It is, however, more largely concerned with the capacity and deflection rate of the springing medium, and also with the static load on the leg, but it is noticeable that some designs appear capable of retaining their good qualities under much wider variations of loading than others.

Track

Taxying qualities are largely dependent on track.

There is no doubt that a wide undercarriage has some great advantages over the narrow type, for a softer longer travel leg may be used without incurring excessive rolling characteristics.

Another advantage is that, with the fitting of wheel brakes, turning on the ground becomes possible with the application of less brake effort at the wheels.

Taxying across a high wind also becomes much easier.

The Divided Undercarriage

If a wide track is to be incorporated in a design a divided undercarriage seems to follow as a natural consequence, and here one may be up against difficulties of structural arrangement, weight and drag, especially in single-engined machines. On a single-engined aircraft which was tested recently at Martlesham, a split type undercarriage was substituted for the standard type with straight through axle. The results were interesting. The split undercarriage was only 9 per cent. heavier than the standard while the level speed performance was increased by 3.5 m.p.h.

From the pilot's point of view the divided undercarriage is a help when taking off or landing cross wind, but has the disadvantage that very high lateral loads may be thrown on to the wheels if a straight pancake landing is made.

There is only one type of aircraft in which the modern tendency to wider tracks has not been followed. In the single-seater fighter class the continual struggle for performance has resulted in a trend in the opposite direction, which from the point of view of ground handling is a step in the wrong direction.

Drag of Undercarriages

There is no doubt that the reduction of the drag of undercarriages provides a field for considerable aerodynamic research.

Tests carried out by the N.A.C.A.[8] in their large wind tunnel show the undercarriage drag of a " Sperry Messenger " aeroplane as being 40 per cent. of the total drag of the full-scale aircraft with the wings removed. The chassis on this machine was of the Vee type with straight through axle. This figure seems excessively high and interference must have been very large. Later tests

[8] N.A.C.A. Technical Note No. 271. " Full Scale Drag Tests on Various Parts of Sperry Messenger Airplanes." F. E. Weick.

in America[9] on a Fairchild cabin monoplane give the undercarriage drag as 25 per cent. of the full-scale machine without wings. The undercarriage was of the divided axle type.

There is no doubt that the lack of a large wind tunnel in England has hitherto delayed research in this direction, since interference plays a big part in putting up the resistance, and this cannot be given its proper value in small models owing to scale effect.

A few design estimates of undercarriage drag have been examined. They give mean figures of about 15 per cent. for straight through axle types and slightly less for divided undercarriages, which in view of the two tests already quoted seem somewhat on the low side.

Many designers, chiefly abroad, have endeavoured to reduce the interference of the various members of the chassis by fairing each side as a whole, enclosing everything in a pair of " trouser legs."

Wind tunnel tests were made on a 1/24th scale model twin-engined monoplane with and without such fairings (see Fig. 29). The addition of the " trouser

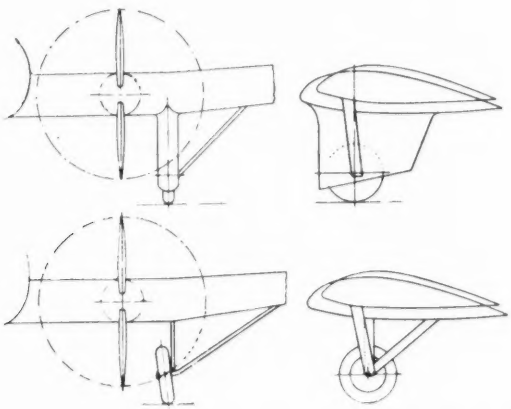

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FIG. 29.

The effect of undercarriage fairings on drag.

legs " reduced the overall drag coefficient of the model from 0.0310 to 0.0287, this being equivalent to a reduction of 30lb. in the full-scale drag at a speed of 100 ft./sec.

The airscrews were not running and the scale effect must have been very large, but the result is quoted for what it is worth.

Wheel Fairings

It has been the custom for some little time past in America to fit wheel fairings or " spats " to aircraft on which performance is considered important.

Wind tunnel measurements of the effect of fitting a form of tail fairing to wheels to produce a better streamline shape were carried out in this country in very early days.[10]

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[9] N.A.C.A. Technical Note No. 340. " Full Scale Drag Tests on Various Parts of Fairchild (F.C.-2 W.2) Cabin Monoplane." W. H. Herrnstein.

[10] R.A.E. Report, B.A., 174. Nov., 1917. " Drag of Aeroplane Wheels with Covers and Tail Fairings."

On a unit consisting of a wheel, axle and strut ends, with rubber cord shock absorber, a saving of 40 per cent. in drag was shown, when a complete tail fairing was fitted to the wheel.

On account, however, of the extra weight and complication, wheel "spats" have been used very rarely until recently. It was thought also that there was considerable danger of mud and grass being thrown up and causing fouling between the fairing and the wheel.

A recent full-scale test carried out on a single-seater biplane of 3,500lb. all up flying weight showed an increase of 3.2 per cent. in top speed, due to fitting the fairings. Their weight was only 30lb., and very little trouble has been experienced in maintenance. The fairing is shown in Fig. 30.

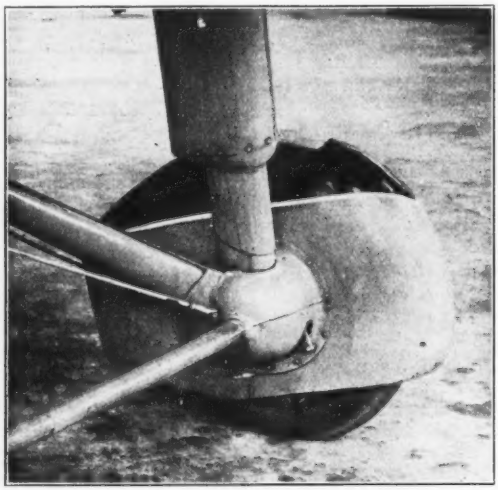

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FIG. 30.

Wheel fairing as fitted to a single-seater fighter aircraft. Full-scale tests showed an increase of 3.2 per cent. in top speed due to fitting these fairings.

The Internally Sprung Wheel

An interesting line of undercarriage development is the internally-sprung wheel, which should give, amongst other advantages, considerable reduction in drag. The whole of the shock-absorbing mechanism being enclosed within the wheel itself, a rigid chassis may be used of somewhat lighter design than is normally necessary. Thus a saving in drag is effected on two counts.

Fig. 31 gives a view of the Dowty internally-sprung wheel, which has been tested recently. In the unit, complete oleo and rubber-in-compression gear is installed inside a disc wheel, and provision is made for fitting brakes as well. The inventor claims a saving in weight of 0.4 per cent. on an aircraft of 3,400lb. equipped with these wheels, and a rigid undercarriage instead of the normal oleo type. The weight of brakes is allowed for in both cases. The saving in drag is calculated as 30 per cent. of the drag of the normal undercarriage at 200 m.p.h.

The main disadvantage of the internally-sprung wheel is that the minimum diameter is limited by the travel required on the shock-absorbing mechanism, and the wheel is thus really only suitable for use with high pressure tyres.

Retractable Undercarriages

There is no doubt that for aircraft where level speed performance is all-important, and where sacrifice in extra weight can be made, the retractable undercarriage is the final answer to the problem of drag. A very good example of such a class is the fast mail carrier.

By a retractable undercarriage in this sense is meant one in which the whole chassis and wheels can be withdrawn into the fuselage and wings to leave a smooth, uninterrupted exterior. It is not to be confused with the type of folding gear used in amphibians, where the wheels are merely raised to clear the water. In this case there is probably an increase of drag due to additional interference.

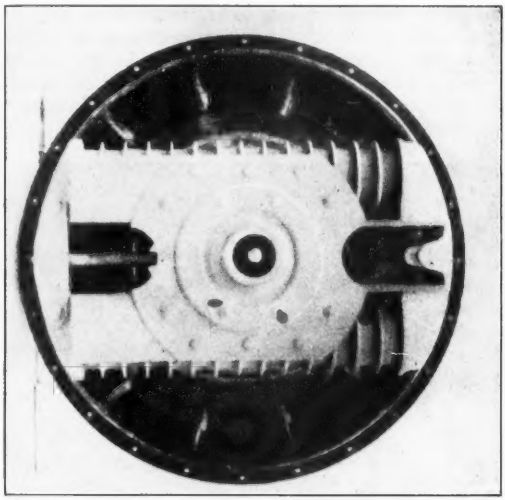

FIG. 31.

Dowty internally sprung wheel, showing the shock absorbing mechanism.

No data has been obtained in this country on the fully retractable undercarriage, and those firms in America which have experimented with this type are not yet in a position to publish the results they have obtained.

As regards the question of weight, some indication of the probable cost in this direction can be obtained from a consideration of the weights of amphibian folding chassis.

Messrs. Saunders-Roe, who have had considerable experience in the design and construction of these units, quote 4.6, 4.75 and 6.25 per cent. as the weights of retractable chassis fitted to three amphibians, expressed as percentages of the all-up flying weights of the aircraft concerned. These figures compare quite favourably with those for normal undercarriages, which vary between 3.5 and 5 per cent.

As regards drag, a very conservative estimate puts the saving as a result of retracting at 15 per cent., giving a gain in top speed of some 6 per cent., the gain in range being 15 per cent.

On the original Fairey long range monoplane, where sources of parasitic drag other than the undercarriage were very small, it was estimated that dis-

pensing with the chassis would give an increase of 1,200 miles on the basic 5,500 miles range for which the aircraft was originally designed.[11]

Several aircraft have been built abroad incorporating retractable undercarriages. A certain amount of mechanical difficulty has been experienced. On one occasion one wheel jammed in the " up " position and the pilot was compelled to land on one half of the chassis only, fortunately without severe injury to himself. Such troubles will, of course, be overcome with development.

The Low Pressure Wheel

As a solution to many of the disadvantages of the high-pressure tyre, the Goodyear Company of America produced and developed the Musselman Air Wheel, known better perhaps in this country by the name of " doughnut " wheel.

This type dispenses with the wheel in its usual form altogether, as the tyre is mounted straight on to the hub. The cross-sectional area, the air volume and the ground contact area are considerably larger than in the case of the corresponding sizes of high-pressure tyre, which enables the air wheel to be used at inflation pressures of 5 to 15lb. per sq. inch instead of the normal 60lb. per sq. inch for the high-pressure unit.

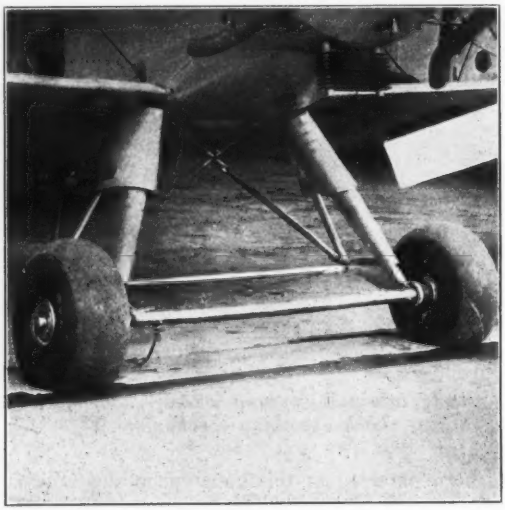

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FIG. 32.

Low pressure air wheels fitted to a quadrilateral type undercarriage.

This lower air pressure undoubtedly makes for better cushioning when landing, but the actual energy-absorption qualities of the tyre are not so great as was originally thought (see page 420).

Attempts were made to dispense with shock-absorbing legs altogether and fit the low-pressure wheels directly to a rigid undercarriage. These in some cases proved unsatisfactory—the aircraft bouncing on landing. In one case failure of the undercarriage took place, though it is possible that this was due to too small a wheel being fitted.

[11] R.Ae.S. Journal, March, 1930. " Range of Aircraft." C. R. Fairey.

The higher ground contact area makes operation in soft or sandy aerodromes very much easier, and taking off and landing has been carried out successfully with these tyres fully deflated.

Although in the small and medium sizes the weights of these air wheels are much the same as those of the corresponding high-pressure units, they are somewhat heavier in the larger sizes.

As regards drag, tests carried out by the N.A.C.A.[12] show that substitution of air wheels of a size corresponding to the high-pressure wheels previously fitted to an undercarriage did not make any difference to the overall drag. This is probably due to the fact that, although the frontal area of the low-pressure wheel is greater, the aerodynamic shape is somewhat better and the interference between the wheel and the undercarriage structure less.

The latest development has been the introduction of the intermediate low-pressure type, which is claimed to possess the advantages of the high-pressure wheel as regards housing brakes with those of the low-pressure type already discussed.

In this respect the history of aircraft tyres has been similar to that of motor car practice, although the problems involved differ considerably.

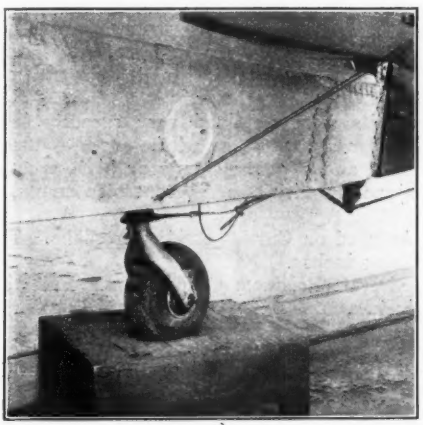

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FIG. 33.
Spring restrained tail wheel fitted to a Wapiti aircraft.

Tail-wheels

The fitting of wheel brakes to aircraft has brought a long-wanted improvement in its train—the tail-wheel in place of the tail-skid. To-day the skid is obsolete except for light aircraft. The advantages of the tail-wheel are many. Manœuvring on the ground is much improved; stresses on the fuselage structure when taxying are considerably reduced; the continual replacement of skid shoes is eliminated, and the havoc wrought on the surface of an aerodrome where heavy aircraft are being operated is a thing of the past.

There are certain disadvantages. The drag is higher, though there appear to be no comparative results showing this; the weight is greater,[13] and, in the

[12] N.A.C.A. Technical Note No. 340. "Full Scale Drag Tests on Various Parts of Fairchild (F.C.-2 W.2) Cabin Monoplane." W. H. Herrnstein.

[13] The D.V.L. publish figures for a Junkers G.24 as follows:—Normal standard skid, 20.5 kg. (45.0 lb.); D.V.L. steerable skid shoe, 23.8 kg. (52.5 lb.); D.V.L. tail-wheel, 24.6 kg. (54.5 lb.).

event of failure of the wheel brakes, the landing run is some 15 per cent. longer than when a skid is fitted.

The problems of the best type of unit and its position in the fuselage have not yet been fully solved.

For best controllability when taxying, the wheel should be as far aft as possible, though this may not fit in with other considerations. The amount of castoring freedom it should be allowed to have is a question open to discussion. A 360° castor and constraining springs to return the wheel to the line of flight is a favoured arrangement, with a release to throw these springs out of action for manhandling on the ground.

To prevent excessive bouncing, which is a common fault, a very low pressure wheel is indicated, with carefully designed shock-absorbing and damping mechanism.

The angle of the axis of castor, and the amount of trail of the wheel, are questions which affect its stability.

Too small an angle between the castoring axis and the ground may cause severe wobble, and it appears that for the best results this angle should lie between 75° and 85°.

Experiments are now being made with a steerable tail-wheel linked with the rudder, but no results have been published as yet.

Comparative Energy Absorption of an Airwheel and the Corresponding High Pressure Tyre

The following results were obtained very recently in tests made by the Goodyear Tyre and Rubber Company, by whose courtesy they are here published.

A 25 × 11-4 airwheel and a 30 × 5 Goodyear high pressure tyre were tested comparatively, in conjunction with two different oleo struts, the details of which are given below.

Oleo Strut A.—As used on Curtiss Robin aeroplane. Fully extended length 36.6 inches. Stroke 4.25 inches.

Oleo Strut B.—Aircraft Products Corporation. Fully extended length 38.6 inches. Stroke 6.0 inches.

RESULTS.

Condition of Test.	Shock absorbing Unit.	Load Factor.	Energy Absorption. High Pressure Tyre. inch lb.	Airwheel. inch lb.	Ratio.*
1000lb. gross tyre load H.P. tyre at 32 lb./sq. in. Airwheels at 7.5 lb./sq. in.	Oleo Strut A	6.5	17200	29100	1.69
1300lb. gross tyre load H.P. tyre at 40 lb./sq. in. Airwheel at 10 lb./sq. in.	Oleo Strut B with light oil	6.5	23600	41300	1.75
1600lb. gross tyre load H.P. tyre at 50 lb./sq. in. Airwheel at 13 lb./sq. in.	Oleo Strut B with medium oil	6.5	31700	52200	1.65

* Ratio of: $\frac{\text{Energy absorbed with airwheel and strut.}}{\text{Energy absorbed with H.P. tyre and strut.}}$

Previous tests carried out by the Goodyear Company with the same units (25 × 11-4 airwheel and 30 × 5 h.p. tyre) in conjunction with a stiff strut gave the following results:—

Gross tyre load = 1,000lb.
High pressure tyre at 32 lb./sq. in.
Airwheel at 7.5 lb./sq. in.
At 3 inches free drop (maximum capacity of h.p. tyre).[14]
Impact energy (h.p. tyre) 6,500 inch lb.
Absorbed energy (air wheel) 9,400 inch lb. } Ratio 1.44.

[14] The maximum capacity is the maximum free deflection of the tyre or airwheel beyond which compression of the tyre structure or excessive springing of the wheel or hub begins.

The maximum capacity[14] of the airwheel was not reached until a free drop of 9 inches had been attained, at which drop the energy absorption was 17,300 inch lb.

Conclusion

The developments of the aeroplane undercarriage have been so many and so diverse during the last few years, that it has been impossible to do justice to them all in one paper.

They have nearly all been concerned with increasing the usefulness of the undercarriage on the ground. One wishes that more could have been written on the developments which will decrease its uselessness in the air.

These no doubt will be the subject of another paper some years hence.

My thanks are due to the Air Ministry for permission to read this paper and to publish many of the illustrations. They are also due to the following:—Messrs. Armstrong, Whitworth, Ltd.; Automotive Products Co.; Bendix Perrot Brakes, Ltd.; Messrs. Boulton and Paul, Ltd.; C. W. Breadmore, Esq., of the Goodyear Tyre and Rubber Co.; the D.V.L. Adlershof; G. H. Dowty, Esq.; Dunlop Rubber Co., Ltd.; the Fairey Aviation Co., Ltd.; Messrs. Handley Page, Ltd.; the Hawker Engineering Co., Ltd.; J. J. Ide, Esq., of the N.A.C.A.; Junkers Flugzeuwerk A.G.; Knorr Bremse A.G.; the Palmer Tyre Co., Ltd.; Pitcairn Aircraft Inc.; the M.T. Department, R.A.E.; the Superintendent of Scientific Research, R.A.E.; Messrs. Saunders, Roe, Ltd.; the Sikorsky Aviation Corp.; Thurstan James, Esq.; Messrs. Vickers Aviation, Ltd.; the Westland Aircraft Works; all of whom have helped me with data and information.

Lastly, they are due to H. L. Stevens, Esq., Squadron Leader McKenna, Squadron Leader Haythornthwaite, F. H. Kelson, Esq., and the test pilots at Martlesham Heath.

Discussion

Major F. M. Green, Messrs. Armstrong-Siddeley's (Fellow): They were very much indebted to the lecturer, because, so far as he knew, it was the first time they had had a paper on that difficult subject which was exercising the minds of designers very much. There was a great number of types of brakes from which to choose, and a great variety of ways of operating them. It might be worth while to refer to a motor car experience of his own, because much the same problems were encountered with the motor car as with the aeroplane. It was true that the weight was not of such great importance with the motor car, but the brakes had to work a good deal longer. Brake operation by Bowden wire was not so bad after all. He had used it for his own car, which he had driven 3,000 miles without adjusting the brakes. They did not feel at all springy. It was a surprise to him, and he believed that the secret lay in having very light loads with rather large wires. He did not think that with the small aeroplanes they could cut out this type of operation; it was by far the simplest method. For bigger aeroplanes, quite obviously, they had to depend on some sort of Servo gear. Here, again, they had motor car experience to guide them. The difficulty of making the brake drum concentric, and keeping it so, was not peculiar to the aeroplane, but was more difficult on the light than on the heavy type. He therefore thought that any type of brake that adapted itself to the hub should be preferred, as being much more likely to lead to steady and easy operation. With regard to the shock-absorbing gear, they had seen what could be done with the low-pressure air wheel. He would like to know whether the lecturer had any experience of using this without shock absorbers. That was the original claim. It seemed to him, however, that it could not be very satisfactory. The duty of the shock absorber, anyhow, on landing, was to absorb shock, not to store it, but apparently the wheel must store most of the energy.

He thought that wheel fairings were only a makeshift, though very valuable. They were more effective in fairing the wheel properly to the undercarriage and struts than in actually reducing the drag of the wheel itself. It must be borne in mind that they were very useful in that awkward place, the junction between the axle and the radius rods rather than in the oleo struts. He was confident that retractable undercarriages would come fairly quickly, and that they would not be very much heavier when they discovered how to make them properly. The wheel fairings now put on were fairly heavy, and it was possible that the saving in weight due to missing them off might go a long way to pay for the necessary gear for retracting the undercarriage.

Captain BARNWELL, Bristol Aeroplane Company (Fellow): The lecturer had suggested that the method of brake operation was left entirely to the designer; this was hardly the case for Service machines. It was laid down that, for Service machines, one hand must be on the throttle lever and the other on the control column, which ruling necessitated that the brakes be operated by the feet or by some " extra " movement of the control column, or (as in the " Knorr " system) of the throttle lever. His company had so far had little experience with brakes, therefore he could not speak with experimentally-determined authority on them.

It might be of interest that in 1919, for the " Safety and Comfort " Competition, the Bristol Company entered an aeroplane for which they designed and made, and to which they fitted, special multi-disc brakes enclosed in large diameter wheel hubs. Unfortunately they were unable to get these brakes to work satisfactorily in time for the competition, so discontinued the experiment in favour of more pressing work, as there was no strong demand for brakes at the time.

He was interested to note the fitting of a tandem-wheel undercarriage to a recently designed aeroplane. The advantages, and disadvantages, of the system were both fairly obvious. The Bristol Company fitted to their " Braemar " aeroplane, in 1918, a tandem-wheel form of undercarriage which actually was satisfactory; but they were discouraged because the bulk of outside opinion, if not definitely hostile, was at least gravely suspicious. As a matter of fact, the undercarriage in question, though drastically handled, never failed directly in tests, although on two occasions the tail skid failed, and on one of these occasions the skid failure led to damage to the undercarriage. This experience corroborated the indications of the List of Accidents shown by the lecturer.

He would suggest that the reason for the apparently increased percentage reduction of landing run (achieved by brakes) for larger aeroplanes, might be because a larger machine was generally of higher wing loading and relatively " cleaner " over all than a smaller one; hence the effect of " ground braking " might be more apparent on the larger machine because the effect of " air braking " would be less. In any case, one would expect the actual length of run, either with or without brakes, to be greater for the larger machine.

The use of wheel fairings, or " spats," was a matter of immediate interest and promised considerable reduction of drag, but they were not too easy to design for either aerodynamic or mechanical satisfaction.

He had lately been carrying out some wind tunnel tests, trying the effect of adding fairings to the undercarriage wheels of a model of an existing aeroplane. Although the model fairings, as originally designed, reduced the free drag of the wheels by 60 per cent., when these wheels with fairings were mounted on the undercarriage, the drag was found to be the same as with the unfaired wheels. Further, when they added faired " bulges " to the insides of the wheel fairings, covering in all the " joints," the drag was increased. Obviously, the trouble was that the various parts were not of happy shapes or positions in relation to one another; but this was only obvious after the wind-tunnel tests.

Again, the weight of wheel fairings was quite appreciable; as Major Green had said 30lbs. was probably a considerable percentage of the weight of the

undercarriage in question, he himself would suggest that it was probably about 30 per cent.

As regards " retractable " undercarriages, their advantages were so obvious that everyone had naturally been brooding over them and trying to produce them for years. But the very important question arose: To where was one to retract the undercarriage? If one had to add large faired " containers " to either body or wings, to receive the undercarriage when retracted, these would certainly add weight and possibly might add nearly as much drag as that of a carefully faired " fixed " undercarriage. It would appear that the so-called " cantilever " low-wing monoplane was about the only type whose lay-out was really favourable, but even with it, the necessary cavities—to house the retracted undercarriage in the undersurfaces of the wing roots—might seriously prejudice the structure of the wing.

The only brakes that the Bristol Company had so far had experience with were the Bendix two-shoe (one Servo) on a single-seater, and the Vickers (two-shoe oleo operated) on a two-seater.

They operated the Bendix brakes by toe pedals, with Bowden and plain cable interconnection. He corroborated Major Green in that this method appeared quite satisfactory for smallish machines, and, if installed carefully and with reasonable robustness, should not get out of adjustment quickly nor be troublesome to adjust.

The Vickers brakes were operated by a hand lever and were automatically " differentiated " by a valve worked by the rudder bar. The brakes were very satisfactory in themselves, but the method of operation was a very awkward one for " taxying."

He considered that for smallish machines brakes operated by toe pedals, with interconnection either by cable or by liquid, gave the greatest promise. For large machines he felt that liquid operation (perhaps air operation) with a definite pressure source would be necessary; having the pressure source, the brakes could be applied by valves which could be spring loaded to afford any desired " feel "; whether then the valves should be directly operated by toe pedals, or say by a " thumb lever " on the control column (with automatic differentiation valve on rudder bar), was an open question; he himself inclined to the former.

Major T. M. BARLOW, Fairey Aviation Company (Fellow): He had little to say on this rather apparently useless part of an aeroplane so far as actual flight was concerned, but a part which was very essential for the start of a flight and the finish. He had been looking at some figures in order to check some of Mr. Scott-Hall's statements. On an average, in military and ordinary civil types, with a standard form of undercarriage, the resistance seemed to vary between five and ten per cent. of the total; therefore, if they could experiment further with retractable undercarriages undoubtedly considerable benefit would be obtained, in spite of possibly a little extra weight and complication. Especially would this be so when they came to a clean machine on the lines of high-speed mail carriers; there the undercarriage was approximately 25 per cent. of the total resistance, and in the case of a long-range monoplane design as high as 30 per cent. There was a tremendous amount to be gained in speed and general efficiency with these types if the undercarriages could be retracted. As regarded brakes, he could not agree with the lecturer's remarks on cable operation. He had tried several types of brake mentioned by the lecturer, including the cable operated, and he did not think that one could say the cable was unsatisfactory. In fact, when properly installed, he agreed with Major Green it was quite equal to modern car brakes; in efficiency there was not much to choose between them, but there was no doubt that a better " feel " was obtained by cable operation on medium-weight aircraft; in the case of the heavier types they would have to go in for some form of " Servo."

Little experience had been obtained of wheel fairings in England up to the present moment. Such information as one had been able to gather led to the

conclusion that it was not so much a question of the wheel drag itself being reduced, but reduction of interference affecting the total resistance.

Considerable improvement is obtained by the fitting of suitable wheel fairings, especially on undercarriages set fairly near a big chord wing. The lecturer had exhibited a slide showing an early aircraft Fairey Twin Fighter, fitted with four-wheel undercarriage and brakes. Major Barlow said that the brakes were cable operated and Bowden controlled, but the idea was discontinued owing to the general belief at that time that brakes would undoubtedly make aeroplanes " nose " over.

Mr. Dowty: He would like to raise the question of low-pressure tyres on air wheels. The lecturer had not mentioned, nor did the manufacturers of that type of equipment advertise, one of the chief advantages of that kind of wheel, namely, the fact that for any given drag load the torque was very considerably reduced because of the smaller rolling radius, which gave a reduced weight of undercarriage, and lighter body fittings. Dealing with the question of brake torque, Mr. Scott-Hall had suggested offsetting the shock absorber strut to partly counter the brake torque. At first sight it would appear that a considerable advantage would be obtained, but during landing and taxying the load in the shock absorber strut varied between 5w. and 1w., and therefore the arm at which the shock absorber strut could act was definitely limited by the high load condition, whereas, when the brake was operating, the load in the strut could fall as low as 1w. If the system were examined in this light the gain would not be more than seven or eight per cent., and he did not think that the complication of offset fittings was justified.

He thoroughly agreed with the lecturer that hydraulic or pneumatic control was very much superior to mechanical operation. Its advantages were even more pronounced for commercial aircraft. The cost of designing mechanical control was considerable, and there were marked complications in mounting such parts as bell cranks and pulleys. For ease of fitting and maintenance mechanical control could not be compared with hydraulic systems.

Considerable difficulty has been experienced in the past with retractable undercarriages, but this had been due not so much to raising and lowering mechanism as to the difficulty of providing an undercarriage which would function reasonably and easily on the ground and yet could be folded into the wings or body. In the past they had been entirely dependent on an undercarriage with a shock-absorber strut of a telescopic nature, which entailed the use of a floating undercarriage structure. The difficulty was the fact that the position of the structural members was definitely limited, because canting of the wheel or toeing in or out of the wheel had to be avoided. The designer was limited to this extent before considering the question of folding. After providing an undercarriage which would function reasonably on the ground, it would be found practically impossible to fold it into the wing without considerable complication. This had been generally sufficient in the past to debar its use. In America there had been developments of retractable undercarriages, he thought on the right line, namely the provision of a rigid undercarriage with air wheels or high-pressure wheels with internal shock absorbers. The structural members could be hinged at any suitable points to ensure that the wheel would fold up clear of spars and other members which might be in the way. He thought that satisfactory retractable undercarriages could be produced if they were considered on the lines of a rigid undercarriage structure. For a considerable time he had been investigating the difficult problem of retracting the undercarriage structure, and to-day he thought that the difficulty could be overcome by the use of a rigid structure.

Mr. Camm, Hawker Engineering Co. (Fellow): He agreed with Mr. Dowty's remarks about brake operation. The hydraulic system was much more easily run than one involving the use of cables, pulleys and so on, and from his experience as an engineer he would strongly support its use.

Squadron-Leader T. H. ENGLAND, Messrs. Handley Page (Associate Fellow): He had been hoping that the lecturer, to whose remarks he had listened with a great deal of interest, would have dealt with the difference in manœuvrability of aircraft fitted with high-pressure tyres as against those of the low-pressure, or balloon, type. In his experience of aircraft fitted with high-pressure tyres he was of opinion that they were more manœuvrable than when a similar aircraft was fitted with the low-pressure, particularly so in the case of the tail wheel.

If the pressure of the tail wheel was maintained at 20 to 25 lbs. the manœuvrability was satisfactory. Below this pressure the manœuvrability was somewhat impaired. Whilst he was all in favour of the low-pressure tyre on the main undercarriage for landing, it had the disadvantage that for taking off the pilot could not tell exactly what was happening, as is possible with the high-pressure tyre.

Turning to the question of brakes, Sq.-Ldr. England said that the greatest problem with which a pilot was faced to-day was how to operate them. So many aircraft had different types of rudder bars. Whereas the system of pedal-operated brakes might prove satisfactory on one type, it did not follow that it was satisfactory on another. He agreed that the method of operation was largely influenced by the type of brake used.

Whilst the operation of pedals appeared to be finding favour on a number of aircraft, he preferred the operation of the brakes by a lever situated adjacent to the throttle, for checking landing run, and for taxying this lever should be set in a certain position whereby by operation of the rudder bar it automatically applied braking effect on the desired wheel. This system is used on certain hydraulic types of brakes and has proved satisfactory.

The lecturer referred to the expansion tube type of brake as possessing the disadvantage that it was impossible for a pilot to " feel " the effect of the braking, if the brake was in the " on " or " off " position. He (Sq.-Ldr. England) was of the opinion that the matter of " feel " was of little importance. Doubtless other pilots present would disagree on this point. Taking into consideration that brakes used on an aircraft of an all-up weight of 5,000 lbs. and over were not used to the extent that they were on motor cars, the only disadvantage in the expansion tube type of brake was the time lag in applying and releasing.

In emergencies the pilot expects immediate response, and for this reason there should be no lag in the operation. Doubtless this difficulty will be overcome in the future, and he felt that there was a great future for this type of brake, in view of its simplicity and lightness over other types.

Captain UWINS: He thought that the interesting formula given by Mr. Scott-Hall at the commencement of his lecture should, if correctly applied, prevent a machine on which brakes were used from nosing over. The part of that formula with which Captain Uwins disagreed, and which he did not think was sound to-day, depended entirely upon the coefficient of friction between the wheel and the ground. That coefficient, the lecturer had told them, had been measured at Farnborough. It must have been with the standard smooth type of wheel which was in use to-day. He had seen a large number of such wheels after they had been in use for some time; they cut very badly, and after heavy rain were perfectly useless for steering aircraft. The greater use of brakes, and the increased dependence on them for steering pointed to the necessity for a treaded or serrated tyre for the undercarriage. That would very likely lead to an increase in the coefficient of friction between the tyre and the ground, and the formula would become valueless. If the treaded tyre was to be used he would like to know whether the lecturer considered it necessary to have some throw-out device for the brakes should the torque become too pressing; because it would be impossible to get a greater angle than 24 degrees on the diagram that he had shown.

The Chairman had asked pilots to give their own impressions as to the best installation of brakes. He had had experience of two operations. Toe operation

on a single-seater aircraft he had found fairly satisfactory. It was difficult to get the pedal in exactly the right position, but it could be put into position, and after an hour or so the pilot became used to it and had little difficulty. Hand operation was very pleasant for direct pull up, but difficult for steering, because it was almost impossible to maintain pressure on the hand lever, which was necessary, and accelerate the machine when trying to turn.

Major Green had asked whether Mr. Scott-Hall had had experience of air wheels being used with no shock absorbers. Two years ago in America, said Captain Uwins, he had the experience of flying and landing on a boat by retractable undercarriage fitted with air wheels. The landing was rather abrupt and the shock absorbing poor, but the air wheels worked well. Great difficulty was found in sinking them, owing to their enormous buoyancy.

Mr. FELLOWES (Dunlops): Both Mr. Scott-Hall and the previous speaker had brought out points which were of direct interest to his company and himself, on the question of tyres. Mr. Scott-Hall had given figures of .3 and .4 as the coefficient of friction taken at Farnborough. Presumably those figures were taken on an ordinary soft grass landing; if they were taken on concrete or asphalt the coefficient of friction might rise to .5, .6, and even slightly higher. Mr. Scott-Hall had mentioned another type of landing, namely, deck landing. If an aeroplane landed on a very smooth deck the coefficient of landing might drop to as low as .1; on the other hand, if the landing deck were of a roughened surface, say, something like a file, then the coefficient would go up appreciably. The last speaker had shown an interest in the question of treaded tyres. People with whom he had spoken had generally agreed that for general purposes of ground landing the type of tread that could generally be put on a tyre was useless, for this reason: The depth of tread of an aeroplane tyre—which, by the way, was very common in America—was only an eighth of an inch, or, say, four millimetres, and when a machine landed on soft ground the broken part of the tread was immediately filled up with mud and became useless. On the other hand, he could appreciate that a light tread of that type would be useful in deck landings. The objection to putting a really effective non-skid tread on an aeroplane tyre, as he saw it—he did not profess to be an aeroplane engineer—was that the big protuberances on the tyre would set up eddies in the air and there would be greater resistance during the flight. With that thought, his company had put out "feelers" to the industry, and the general opinion was that for ordinary landing machines a plain or smooth treaded tyre was best.

Mr. Scott-Hall had referred to the low-pressure tyre, and had also mentioned the danger of the machine breaking through tipping on its nose. He (Mr. Fellowes) could visualise that, with a very low-pressure tyre having a large flexible or flabby body, on application of the brakes the tyre would come to a standstill in contact with the ground but the velocity of the machine would tend to take the axle forward, assisted by the flexible tyre, and in that connection there would appear to be more liability for a machine to turn on its nose. In view of which the Dunlop Company had brought out the Intermediate Low-Pressure Tyre, which, as Mr. Scott-Hall had mentioned, gave advantages over any other type of tyre.

Flight-Lieutenant STANILAND: He was of the opinion that cable-operated brakes up to about 6,000 lbs. were much more pleasant to use, taxying could be carried out more easily, and the pilot did not tear up the surface of the aerodrome, as was liable to happen with air brakes, or oleo brakes, fitted to the machine. On a wet and slippery aerodrome the use of oleo brakes made turning very difficult without locking either wheel, thereby damaging the aerodrome when soft.

Mr. P. E. HALL (Bendix-Perrot Brakes, Ltd.): He did not agree that cable operation has any severe disadvantages. It is only on very large aircraft that any difficulty is experienced in designing a suitable cable or mechanical system. On all normal sized aircraft the layout is simple and certainly much less com-

plicated and lighter than any existing hydraulic method of operation, both to instal and maintain.

It would seem that Mr. Scott-Hall has exaggerated the problem of cable stretch. This is more a question of careful design than any inherent defect of the cable system. As is well known, the Bendix Brake Company are now manufacturing many thousands of automobile brakes weekly and in all cases cable and conduit operation is employed, and no troubles are experienced with cable stretch. The experience of leading aeronautical engineers at this meeting upon the question of cable operation is extremely interesting. They are unanimous in their contention that cable-operated brakes are perfectly satisfactory in service. Furthermore, pilots of great experience in all types of brakes have corroborated what the engineers have said. They have also laid stress upon the fact that the " feel " is undoubtedly better with mechanically-operated brakes; in fact, from their remarks, and those of the lecturer, it would seem that this system is the only one that provides this feature, which is a vital one.

His company are now making all their brakes with long internal levers, so as to avoid heavy loading of the cables, in fact the maximum loads in the cables for a retarding force of .4 W. is between 50 and 100 lbs. This is a moderate figure. It has been found that the old type of cable and conduit is unsuitable, and they are now using a cable with a centre wire core and a smooth exterior. The conduit is also of special section resulting in a cable system which is more efficient owing to the smooth contact surface provided by the new type of cable and conduit, whether the control is straight or bent.

They were working along the lines of foot-pedal cable control for naval and military machines with an additional hand-brake lever for parking purposes, but for the larger types of civil machines they favoured a hand-lever operated brake and for steering the plane on the ground the usual movement of the rudder bar for aerodynamic control is employed. We consider that for all aircraft up to 20,000 lbs. a machine can be satisfactorily braked by means of a mechanical operating system, either by an all-cable hook-up or combination of cable and rods. For machines over this weight they would undoubtedly have to consider employing some form of power brake or booster.

The type of control due to Mr. H. L. Stevens, and described by the lecturer, is extremely ingenious and has many points of appeal. He would like to know if it has been tested on any machine using any of the three methods of operation.

With regard to the presence of oil on brake shoes, this should not be tolerated in any braking system and all our brakes are provided with shields which catch the oil or grease and prevent it from getting on the shoes.

Mr. BRAMSON (Fellow and Member): The Chairman had invited pilots to give their opinions as to methods of operation, and the lecturer had pointed out that, due to the limitation in the number of limbs available, it was a serious problem. Mr. Bramson found himself in disagreement with the lecturer when he said that one particular system to which he referred had been found to be no good, namely, the one in which the brake operating mechanism was coupled to the joystick. One particular instance had been given where that might lead to danger, but it could be avoided in the following manner: If the amount of upward elevator movement that was required for aerodynamic purposes was, say, 35 degrees, and a further 10 degrees was allowed, and if the brake was so arranged that it only came into operation when the stick had been pulled back to the fullest extent which could ever be required for aerodynamic purposes, then it was still possible to have the joystick right back in the aerodynamic sense and yet not apply the brake. Then if necessary the stick could be pulled hard back, thereby applying the brake, which could be so adjusted that the force of the return spring could be clearly felt in the stick and the pilot would therefore know whether he was braking or not. He had had experience of that method in an experimental

aircraft in which the differential control of the brakes was achieved by an over-riding coupling to the rudder bar. This system had the advantage that one hand could be on the throttle control and the other on the stick, and complete control was obtained of the throttle, the elevator, the straightforward brake, and the differential brake.

One would like to hear the lecturer's opinion as to what was the kind of force-deflection diagram which gave the smoothest type of landing and taxying. At the present time it seemed to be rather a matter of accident whether, when a new undercarriage was designed, it would result in comfortable taxying, and landing, or whether it would subject the machine to rough treatment. It was chiefly a question of the force-deflection diagram, and also depended on the amount of dash-pot effect. In these days of autogyros, and the amazing things which had been done with them, it would be interesting to see what would happen if an autogyro type of undercarriage were fitted to a standard aircraft controllable beyond the stall. He had flown a Moth fitted not only with slots but with deflectors; it was so much under control when stalled that he felt that, if the undercarriage would only stand it, he would not mind going the whole of the way to the ground in the stalled condition.

He inquired of the lecturer, an expert on stalled flight, the rate of vertical descent at which one might expect to arrive on the ground and the increase in the weight of the undercarriage necessary to cope with that rate of descent.

Mr. Bramson drew Mr. Scott-Hall's attention to the fact that not only for the purpose of housing the retractable undercarriage, a very desirable feature, but also from the point of view of increasing the angle α the low-wing cantilever monoplane seemed the ideal machine. The low-wing monoplane had a much lower centre of gravity than either the biplane or the high-wing monoplane. The angle α was increased, without an increase in the tail load, by lowering the centre of gravity instead of putting it further back in relation to the wheels. That was his reason for suggesting that the low-wing monoplane was, from the braking point of view, the ideal type of plane.

Flight-Lieutenant ALLEN: While disclaiming any intention of rudeness towards designers, he thought it was about 17 years since he had seen aircraft fitted with wheel brakes. If they took much longer he suggested that something in the nature of reversible airscrew blades would make wheel brakes a back number and quite unnecessary. Had the lecturer knowledge of any experiment having been made embodying the idea of lowering a skid to take the weight of the aircraft off the wheel and pull it up that way? He suggested that it could be done quite simply, with less complication, and possibly with less drag and weight, than with some of the new brakes which had been illustrated. He would be glad if the lecturer would inform him whether consideration had been given to any scheme for a hinged rudder bar, normally kept in a straight line by a spring, for use aerodynamically. Extra pressure applied to the rudder bar bent it about the hinge and applied the brakes, thus simplifying control.

Mr. MANNING (Fellow and Member of Council, who took the chair on the Master of Sempill leaving): He had noticed that every conceivable method of operation of brakes had been mentioned that night, with the exception of electrical operation. That method might have certain advantages, and he would like to ask the lecturer whether it had been tried. In the interest of historical accuracy he must query the statement that the old undercarriage shown was a Bleriot. He believed it was a Deperdussin.

Air Commodore CHAMIER (*communicated*): It is admitted that hydraulic or pneumatic systems are needed for the bigger machines; also that brakes are required for parking as well as for arresting motion. A combination of the two in one system leads to two difficulties: (1) the brakes are applied by opening a valve to a pressure tank, which results in no "feel"; (2) when "parked"

the braking piston is under constant and very high pressure, which puts a very great strain on the plunger washer and leads to leaky valves and general unreliability. He suggested that the two systems should be separated. It will then be possible to make the parking brake mechanical, because it is only used when the undercarriage is at rest and long travel and lack of a steering feature are both unobjectionable. (This separate system will also provide an emergency stand-by for arresting.) They could now simplify the hydraulic system by doing away with the tank, and if they merely had a system filled with oil under little or no pressure they could use the column of oil for direct application of a Servo shoe, thus getting " feel " and complete reliability.

Mr. N. D. NEW (*communicated*) : The question of the efficiency of air wheels being used on rigid undercarriages did not appear to be definitely answered. He had noticed that an account of experiments testing the shock-absorbing and storing properties of these tyres was given in N.A.C.A. Report No. 381. This report appeared to have been overlooked by those who spoke at the lecture.

He thought that the figures from this report might be printed in the JOURNAL to clear up any doubt which existed on the matter.

REPLY TO DISCUSSION

Mr. SCOTT-HALL: So many points had been raised in the discussion that he would deal with some in writing. He was very glad that the discussion had turned mainly on the question of the cable versus hydraulic and pneumatic methods of brake operation. He regretted that there was no one present, with the exception of perhaps two pilots, who could give an opinion on the maintenance of brakes under service operational conditions. Many had spoken from the aircraft constructors' point of view. They used the brakes first before maintenance troubles had time to start. The testing establishment used them next and found maintenance troubles arising in the case of cable-operated brakes, and consequently did not like them so much. He would very much like to hear the opinion of some pilot who had used cable-operated brakes in a country where the conditions were more difficult than those that the aircraft constructor or the testing establishment had to face here.

With further regard to the question of cables, he thought that one of the main difficulties in using them in aircraft, as compared with motor cars, was the fact that the relative movements of the various parts of the undercarriage in the case of an aeroplane were much greater than they were in the case of a car. He thought that had a great bearing on the question.

Major Green had inquired about the possibility of using shock-absorbing gear without oleo legs. In the only case within the lecturer's knowledge where an aircraft was tested without oleo legs the result was not satisfactory, as the undercarriage failed when the oleo legs were dispensed with. He must admit, however, that it was a very heavy landing, and it was hardly a fair test of the low-pressure wheel. The energy absorption of a low-pressure air wheel was roughly between one-and-a-half times and twice that of a high-pressure wheel of the corresponding size. He was particularly interested in Captain Barnwell's reference to interference. It was safe to say that at the present time we knew very little about that question in regard to undercarriages. It was one of the main points that needed to be cleared up as far as chassis drag research was concerned. The main item of the drag of this unit was due to interference, as was shown by a comparison of designers' estimates of undercarriage drag and those few actual measurements which had been made so far.

Major Barlow had raised the question of the variation of undercarriage drag as between military aircraft and, for example, the long-range monoplane. Mr. Scott-Hall thought that Major Barlow's remarks illustrated the shortcomings of

the average military aircraft at the present time from the point of view of drag, since the drag of the undercarriage represented so small a percentage of the total drag in the case of this class of aircraft in comparison with a reasonably clean monoplane. In regard to Major Barlow's statement that pilots were afraid to use the brakes on the old Fairey Fighter machine with the four-wheeled undercarriage, he could only say that a pilot had told him in conversation that the brakes were delightful: "You simply jammed your foot on hard and nothing happened."

He was grateful to Mr. Dowty for raising the point about the offset shock absorber. It had not occurred to him; he saw the scheme and thought it was a good one from the points of view of simplicity and low drag. He would like to answer Mr. Dowty in writing, after he had given the matter more thought. He was very interested in Mr. Dowty's remarks about retractable undercarriages and the advantages to be obtained from a rigid structure. In answer to Squadron-Leader England, it was the first time he had heard the manœuvrability of a low-pressure wheeled undercarriage criticised. He thought that 25 lbs. per square inch was too high a pressure for a tail wheel type, having regard to bouncing troubles.

Turning to the question of "feel" with pneumatic brakes, it was possible that in the case of civil aircraft and single aircraft landing alone, "feel" was not very important. It was very important, however, in military operations; aircraft might be landing in formation and if a pilot could only have his brakes full on, or right off, it rendered it very difficult for him to keep proper distance. Notwithstanding Captain Uwins's criticism, he thought that the criterion that he had given for immunity from overturning was not rendered invalid by a change of the coefficient of friction between tyre and ground. The point was that the angle must not be less than $\tan^{-1}\mu$. μ could be anything. He agreed that the coefficient of friction would probably go up with the treaded wheel. He thought that the treaded wheel would come. He had been asked by another speaker about the effect of treaded wheels. The only aircraft, to his knowledge, on which brake tests had been made with such tyres fitted was the Handley Page "Gugnunc." The results were astonishing, since the landing run was apparently reduced by no less than 83 per cent. when the brakes were used. He thought that that actually represented the difference between the normal landing without brakes and a fully stalled landing with brakes.

Mr. Fellowes had raised the question of the extra danger from overturning with low-pressure wheels. He did not think there was any appreciable danger; the aircraft when first landing was partially air-borne, and the skidding which applied in the case of high-pressure wheels applied equally to low-pressure wheels. He had not heard of any undue overturning tendency on aircraft fitted with low-pressure wheels, when the brakes were applied.

In answer to Mr. P. E. Hall, experiments were being conducted at the present time with Mr. Stevens's method of brake control.

A slide was then exhibited (Fig. 28) which the lecturer thought was a good practical answer to Mr. Bramson's query. It showed the load deflection diagram for a very good shock-absorbing leg—of which Mr. Scott-Hall thought that most pilots would say that it was one of the best they had ever tried. He would like to discuss the control column method of operation of brakes further in writing, but he confessed that it was a method he did not like.

Dealing with the question of stalled flight, the lecturer said that a rate of descent of as much as 1,500 to 2,000 feet a minute could be attained. The only undercarriage, within his knowledge, that had been designed to carry out stalled landing was extremely heavy, and also extremely cumbersome owing to the excessive travel necessary on the oleo legs. It provided for landing at a vertical velocity of 30 feet per second. It was intended for three aircraft specially designed

for stalled landing, but unfortunately, or perhaps fortunately, all three machines were crashed before the stalled landings could be carried out.

Captain Barnwell's remarks on the " Braemar " tandem undercarriage had been of great interest. The lecturer had heard from another source that the same skewing difficulty had been found with this undercarriage as occurred in the case of the Junkers design.

He did not agree that the wing loading of large aircraft was higher than that of small machines—in fact if anything, he thought that in the case of large biplanes it tended to be lower. He thought that the longer landing runs of large aircraft were due to the fact that the angle of attack of wings and fuselage was less than for small ones, when running along the ground. This, in turn, was due to the fact that the undercarriage of a large multi-engined aircraft was usually much shorter in relation to the distance between wheels and tail support than it was on a small aircraft.

Except in the case of monoplanes, he did not agree that the big aircraft was relatively " cleaner " in design than the small machine.

In further reply to Mr. Dowty on the subject of the offset strut, he agreed with what Mr. Dowty had said but still thought that the saving in drag, coupled with the eight per cent. saving in weight, was worth the complication of the offset fittings.

He had been very interested in Captain Uwins's remarks on the subject of the use of air wheels in America, and his experience of them fitted to an amphibian. He did not think that any throw-out device for the brakes would be necessary with the treaded tyre. He himself did not think that an automatic release was required under any conditions, since the pilot would instinctively release the brakes himself if he felt the aircraft overturning.

He agreed with Mr. Fellowes that the treaded tyre, whilst of little use on the average muddy aerodrome, would be a help in deck landing. He did not think that the resistance of the tread itself would be a serious question. Under certain aerodynamic conditions a roughened surface was actually an advantage, as in the case of a golf ball.

He was sorry that Mr. P. E. Hall thought that the problem of cable stretch had been exaggerated, but he could not agree with him, since his statement of the case had been a direct result of his own experience, and he was strongly in favour of the hydraulic and pneumatic methods of operation for any but small aircraft. However, he thought that the long internal lever would certainly help to overcome the difficulties and he regretted that he had not been able to show a slide of the latest mechanism at the lecture. He agreed that the " feel " was best with mechanically-operated brakes.

With regard to the method of brake control using the control column for operation which Mr. Bramson had described, he thought that this was an improvement on the system he had in mind when he wrote the paper. Something very like Mr. Bramson's system had, he believed, been fitted to an aircraft, and had not been reported on adversely by those who had flown it. He felt, however, that any movement of the control column *forward* to counteract overturning was contrary to the natural instinct of a pilot, and Mr. Bramson's scheme did not solve this difficulty. He agreed that the system had the great advantage that the pilot need have no extra controls to operate.

He was interested in Mr. Bramson's remarks about the control when stalled of the Moth fitted with slots and interceptors. His own impression of the problem of making stalled landings was that the great difficulty now lay in *longitudinal* control and stability, since the lateral question had been more or less settled.

Mr. Bramson had inquired as to the increase in weight of the undercarriage necessary to cope with a rate of descent such as one might expect in a stalled

landing. The following particulars of the aircraft he had referred to as having been designed for such landings might be of interest:—

All up flying weight of aircraft	= 2,800 lbs.
Top level speed	= 76 m.p.h.
Weight of undercarriage + tailskid	= 208 lbs.
Estimated drag of undercarriage* at top level speed ...	= 60 lbs.
Maximum estimated landing velocity	= 31 feet/sec.
Travel of oleo legs	= 2.87 feet
Maximum estimated landing acceleration with undercarriage as designed	= 5.0 g.

He agreed with Mr. Bramson in regard to the advantage of the low-wing monoplane for fitting brakes.

In reply to Flight-Lieutenant Allen, he had no experience of a skid being used in the way suggested. He did not think, himself, that such a scheme could be carried out with a saving of drag and weight over the ordinary types of wheel-brake that were in use at present. So far as the lecturer knew, the hinged rudder bar had not been tried.

Mr. Manning had suggested electrical operation of brakes. The lecturer had never heard of it being tried. It had obvious advantages from the transmission point of view, but he thought that the question of weight was the great drawback.

He apologised for his slip in describing the old undercarriage as a Bleriot. It was in fact a Deperdussin, as Mr. Manning had said.

In reply to Air Commodore Chamier, he agreed that a separate mechanical system for parking and to provide emergency braking was very desirable, but thought that it could only be used on very large aircraft where the additional weight would not be a serious item.

In reply to Mr. N. D. New, a reference to N.A.C.A. Report No. 381 will be found in a footnote in the paper. The comparison between high-pressure tyres and air wheels given in that report was purposely not quoted because the figures have been superseded as a result of tests since carried out in America. The later comparison is given in the appendix.

* 1.5 × drag of a normal type undercarriage. Without fairings the drag of the undercarriage for stalled landings is 165 lbs. at this speed.

AIRCRAFT AND THE FIRE PROBLEM

BY

R. A. DENNE

(Lecture read before the Bristol Branch.)

Fire control has two phases, prevention and cure. Of these the first is obviously the most important, but equally obviously serious attention must be given to the second.

Great advances have been made towards the minimising of the fire hazard as it affects aircraft. Previously inflammable components have been replaced by ones of metal; tanks have been made much less prone to disintegrate in a crash, and the press has provided us with a non-inflammable fuel.

It is not my intention to-night, however, to deal with this aspect of the case; it has received a great deal of attention and is constantly before you as aircraft designers. I propose to elaborate the subject of curing those cases we are unable to prevent.

The subject of fire extinction has been curiously neglected scientifically. Recently, one must admit, some attention has been bestowed upon it, but attention of rather a haphazard nature.

One still sees in Patent Specifications that the proposed material can be applied to dry-cleaning, de-greasing or fire extinguishing. The leading chemical houses, claiming from a frothing agent for the flotation process will add, quite regardless of the particular needs of a fire extinguishing froth, that the agent is suitable for fire extinguishing.

I do not think I shall waste your time if I summarise briefly the nature of fire extinguishing media. There are two distinct ways at present understood of attacking a fire; the first, by preventing the continuance of combustion by withdrawing or restricting the supply of one of the reagents, and the second by cooling the burning material below its ignition point.

The most general method is the second, and the success of water as a fire extinguishing agent depends, not only upon its availability, but upon its high specific heat and extraordinarily high latent heat of vaporisation. To a comparatively very small extent water extinguishes by mechanical impact and by the formation of oxygen-excluding vapour, but these effects are neglibible compared with its cooling propensity.

Where large masses of combustibles are involved, and by that I mean where combustion is taking place throughout large masses, a very great degree of heat-absorption is necessary to lower the whole to a temperature below the re-ignition point. For large quantities of solid materials, water is the best extinguisher.

Water, however, is unsuitable for use on many materials, especially those liquids with which it is immiscible and than which it is heavier. Some authorities, reasoning by analogy, believe that water is unsuitable for use on any inflammable liquid, but this is not so. Water is the best extinguishing agent for carbon bisulphide, for example, for while it is practically immiscible with this liquid, it is lighter than it and it has the added merit of dissolving the sulphur dioxide produced when the liquid burns.

An interesting train of thought starts at this point. Water shows a marked reluctance to spread out into a uniform layer on the surface of carbon bisulphide.

That is, of course, a surface-tension effect, and the reluctance can be materially reduced by reducing the surface-tension of the water with one or other of the commonly known agents, among which is soap. This prompts the thought that water probably exhibits a similar reluctance to spread out on other substances, solids as well as liquids, and the existence of wetting-agents in the textile industry bears out the hypothesis. We are, therefore, led to the conclusion that water would probably form a more intimate contact with combustible substances, or in other words, "more of it would stick," if its surface-tension were reduced, and we are tempted to suggest that for portable water extinguishers the modification might be an advantage.

However, that is a digression. At the moment we are more concerned with those materials for whose extinction water is unsuitable. For these the method of attack has generally been blanketing away the oxygen necessary for combustion, and this can be done either by means of foam or by means of non-inflammable vapour, both systems being in use. For convenience we will deal with foam first. Curiously enough, although foam extinguishers are familiar articles of commerce, very little is known about foam itself. It is quite safe to say that there is not a manufacturer or vendor of foam machines or foam powders who can describe with any accuracy the factors governing the creation or destruction of foam. When asked he will talk about the reduction of surface-tension and the strengthening action of alumina and liquorice, he will also perhaps say that the collapse of foam is due to evaporation or more generally to coalescence of the bubbles, but that is all.

In order to produce a good, that is to say a lasting foam, one must understand the cause of its disintegration. This may be evaporation, or a tendency on the part of the liquid to aggregate, or diffusion through the walls of the bubbles of the gas with which the bubbles are filled. This latter possibility is well within the bounds of reason, foams are generally gassed with carbon dioxide which, of course, thanks to its solubility in water, will quite rapidly diffuse through a film of this liquid.

I am afraid that I am tempted to enlarge each section of my subject as I come to it, but I believe that you are more interested to know the inner mechanism of the various points and the problems which confront the student than to listen to a broad account of the well-known methods of fire extinction in common use.

Admittedly some advances have been made in the technique of foam; for instance, a foam now exists which will float upon the surface of alcohol and acetone. In the Aircraft Industry this is of interest since the ketones and alcohols are used to a large extent as solvents. Here again the precise action is uncertain. It is believed that an ordinary foam is de-hydrated by alcohols, ketones and aldehydes, since these classes of compound have in general a strong affinity for water. The success of the existing alcohol-resisting foam, whose constitution is based upon this hypothesis, goes to show that the hypothesis is probably correct, but there are other properties besides an affinity for water possessed by these families which might well be responsible for the phenomenon. For instance, they are all known as disperse agents. However, the only point which emerges of any practical importance at the moment is that all foams are not the same foam, and that it is time for users to exercise discrimination in its selection.

Consider the question of blanketing a fire with non-inflammable vapour. We have the choice of using the vapour direct, that is to say, as compressed gas, or as liquid which is easily vaporised. The first alternative is not worth much attention, although it would be, in my opinion, more reasonable to use compressed nitrogen in permanent installations covering the bunkerage of coal than it is to use carbon dioxide. The reason for this preference is that under the conditions which obtain in a burning bunker, the passage of carbon dioxide through the ignited coal would probably result in the formation of quantities of

carbon monoxide which, in addition to being dangerous physiologically, is inflammable and apt to originate an explosion.

Of the easily vaporisable liquids carbon tetra-chloride is the best known. I have been indulging recently in some controversy on its toxicity and on the toxicity of its decomposition products, and I will summarise my views as follows. In itself pure carbon tetra-chloride can be regarded as non-toxic, allowances of course being made for possible idiosyncrasies. As regards the toxicity of its decomposition products, since these may contain phosgene in small quantities and do contain traces of free chlorine they should be regarded as toxic, but dangerous only in confined spaces and where the operator has such physical control and moral determination that he will remain in an intensely irritating atmosphere for a prolonged period.

The success of carbon tetra-chloride as a fire extinguishing agent depends almost entirely upon the blanketing action of its vapour. The more rapidly the liquid is converted into vapour the better, that is quite clear. It follows that since carbon tetra-chloride has a comparatively high boiling point (76°C.), it must be applied in an easily vaporisable form. Certainly some good purpose is served if the liquid is simply poured over the fire, some at least of it may be vaporised rapidly by the heat of the combustion. But it is surely much more effective to break up the liquid first into globules of small size, since the rate of evaporation depends upon surface area, among other things.

A liquid which is attracting increasing attention is methyl bromide, and it may be interesting to you to discuss some of its peculiarities. First of all, while, as you know, carbon tetra-chloride is a product of methane, in the molecule of which all four hydrogen-atoms have been replaced by chlorine, methyl bromide is a mono-substitution product of methane, only one of the hydrogen atoms being replaced by bromide, giving the formula CH_3 Br. The immediate effect of this is that methyl bromide produces weight for weight more vapour than carbon tetra-chloride in the inverse proportion of their molecular weights, that is 152-95. While 152 grammes of carbon tetra-chloride are required to produce 22.22 litres of vapour, only 95 grammes of methyl bromide are required to produce the same amount. Since the specific gravities of the liquids lie fairly close together, methyl bromide produces volume for volume more vapour than carbon tetra-chloride, 100 cubic centimetres of methyl bromide giving 40.4 litres of vapour as against 23.6 produced by 100 cubic centimetres of carbon tetra-chloride.

This is not all. Methyl bromide boils at $4\frac{1}{2}$°C., carbon tetra-chloride at 76°C., consequently the vapour will be produced very much more rapidly in the case of methyl bromide. At ordinary atmospheric temperature, and if both liquids are supplied with heat at a rate commensurate with their latent heats of evaporation, their rates of evaporation will be proportional to their vapour pressures. As a matter of interest let us suppose that the atmospheric temperature is 30°C., at which temperature carbon tetra-chloride exerts a vapour pressure of 143 mm. of mercury. Whatever the atmospheric temperature provided it is above 4.5°, methyl bromide will be very slightly below 4.5° if it exists as a liquid at atmospheric pressure and therefore will exert a vapour pressure of about 760 mm. of mercury.

Their rates of evaporation then will be in the proportion of 143 to 760, methyl bromide will vaporise about six times as rapidly as carbon tetra-chloride.

It is often said that these low boiling point liquids extinguish a fire by freezing it. That, of course, is nonsense, actually they have less cooling effect upon the fire itself than has water. The actual amount of heat absorbed in raising a liquid from any given point to any other given point, respectively below and above its boiling point, will be the sum of the specific heat of the liquid times the difference between the original temperature and its boiling point, the latent heat of vaporisation, and the specific heat of the vapour times the difference between its boiling point and the ultimate temperature. The fact that liquids of the methyl bromide type produce a considerable fall of temperature by their evaporation does not affect the main issue; the temperature drop depends upon the

difference between the rate that heat is absorbed by the evaporating liquid and the rate at which it is supplied from external sources. The rate at which heat is absorbed depends upon the temperature, and the temperatures with which we are dealing are well above the boiling points of all the liquids we are likely to consider.

This result is confirmed by the popularity of water as an extinguishing agent and we are in a position to express the axiom that the fire extinguishing value of a liquid purely as a cooling agent depends upon its specific heat and its latent heat of vaporisation and not to any great extent upon its boiling point.

Before we leave this aspect of the case we might consider another very useful liquid, carbon dioxide. It has several points in its favour; it is odourless, non-toxic and quite harmless to the vast majority of materials. Its boiling point is very much lower than either of the previously discussed liquids (−78°C.), and therefore it should be very much better as a rapid vapour producer than either methyl bromide or carbon tetra-chloride. Unfortunately for our calculations its melting point is higher than its boiling point, and the result of this is common knowledge. Liquid carbon dioxide solidifies almost immediately the pressure falls, and the solid sublimes without passing through the liquid state. The vapour pressure of the solid is not high and its state of aggregation is large, consequently it will vaporise relatively slowly. In fact, a piece of solid carbon dioxide will last for several hours if allowed to sublime freely at room temperature.

To revert to methyl bromide and carbon tetra-chloride it is quite clear that their natures call for different methods of application; while carbon tetra-chloride with a boiling point well above atmospheric temperature needs a high degree of atomisation, such a degree is not only unnecessary in the case of methyl bromide but definitely disadvantageous, since the liquid will have to travel through the air for some distance before it reaches the fire.

Now one of the best means of atomising a jet is to dissolve a gas under pressure in the liquid in question, so that when the pressure is released the violent effervescence which naturally results disintegrates the jet. This means is employed advantageously in an existing type of carbon tetra-chloride extinguisher, carbon dioxide being the gas used since it is very soluble in the liquid.

However, we do not want this effect with methyl bromide, and since carbon dioxide is very soluble in this also, we are on theoretical grounds debarred from its use as a propellant. It is interesting to see that an existing type of methyl bromide machine uses nitrogen in this capacity.

It is possible still further to reduce the tendency of methyl bromide to evaporate *en route* by adding to it a liquid of considerably higher boiling point. The function of this added liquid is to act, as it were, as a carrier, and not to form a constant boiling point mixture whose boiling point is higher than that of methyl bromide. If it were to do this, it would destroy one of the most valuable features of methyl bromide, its volatility.

The number of liquids which can be used in this capacity is limited to those which are (*a*) miscible with methyl bromide (*b*) of high boiling point and (*c*) of low melting point. This last requirement is important, since the temperature falls considerably as the methyl bromide escapes from the machine and any adulterant whose melting point was within the temperature range might solidify and choke the jet.

Pentachlorethane fulfils the conditions fairly well, that is to say, it is soluble in methyl bromide, its boiling point is 159°C. and its freezing point −22°C., but it has the drawback that it is a chlorine compound, and therefore there is the possibility that phosgene may be among its products of decomposition.

In spite of the theoretical possibility that a substance, $COBr_2$, analogous to phosgene and still more dangerous, exists, as far as one can determine it has never been isolated and therefore appears to have no individual existence in practice. It is clearly to our advantage to confine ourselves to bromide compounds,

but unfortunately no bromide compound adequately fulfils the conditions we are imposing.

This need not unduly perturb us for methyl bromide alone will give a jet long enough for all practical purposes; for instance, at 75lbs. pressure it can be projected 30ft. or more from a nozzle 1/32in. in diameter and for a hand extinguisher a longer jet than this is quite unnecessary, in fact an axiom which is worthy of more note among manufacturers and those authorities who specify their requirements in detail, is that a hand extinguisher should not be used at all upon any fire which one cannot approach to within about 10ft.

The extinction of fires in aircraft differs very slightly from the extinction of fires anywhere else; the only two features which are uniquely shown in the former are (1) the restriction imposed upon the weight of the apparatus, and (2) the restriction on the mobility of the operator.

Both these restrictions apply to fires in the machines themselves and while the machines are away from permanent aerodromes. Aerodrome fires are in every way similar to other kinds of hazards met elsewhere and there are no restrictions imposed upon the methods of extinction.

Cases have been known of aeroplanes taking fire while in flight, but the great majority of aircraft fires take place as the result of a crash. Now we can admit without further ado that in the event of a serious crash in which the petrol tank has burst and the result has ignited there is nothing we can accomplish with apparatus carried on the aircraft. The permissible weight is obviously so small, the volume of inflammable fuel so large, its dispersion so great and the co-operation of the pilot such an improbable factor that the ultimate result is a foregone conclusion.

We can concern ourselves with smaller outbreaks however, and several firms have put on the market apparatus for this purpose. The Total Gesellschaft of Berlin produce an apparatus using carbon dioxide, whose container can be opened either manually or by the ignition of suitably placed celluloid detents; Wintriel of Bensheim and Phylase of Berlin produce carbon tetra-chloride plant working on much the same principles. Without wishing to criticise such developments as these, I am compelled to suggest that the particular problems presented by aircraft have not received their due consideration, if they have received any at all. For instance, our own Air Ministry would not entertain the inclusion in an aircraft's equipment of a cylinder containing gas under a high degree of pressure.

In fact, the special requirements which an aircraft extinguisher should be designed to fill can best be understood if I explain what the Air Ministry specify and the steps that have been taken to meet their specification.

The Air Ministry call for an extinguisher which will discharge its contents automatically into the engine compartment either in the event of fire breaking out therein, or of a crash; which will operate either into the engine compartment or into the cockpit at the will of the pilot; which shall carry a specified amount of extinguishing medium; which shall weigh, complete in every detail, less than 12lbs.; which shall not contain a high degree of pressure; which shall be compact, simple and reliable and which shall operate in any position in which the machine may happen to be.

Without discussing at length the considerations which govern the choice of medium and its quantity, we can take this item as 1 quart of methyl bromide, weighing 4lbs.

The first and most difficult problem immediately confronts one. How is this liquid to be carried so that it is always available under considerable pressure and regardless of the position of its vehicle?

Any container of the soda water syphon variety is excluded by the fact that normally it will only function right side up and that to remedy this defect a complex system of pipes and valves must be used, which besides being heavy are uncertain in action. It has been seriously suggested that the entire container should be mounted in a system of gimbals, but the thought of a weight of

5 or 6lbs. free to swing as fancy takes it is not a very satisfying one. Actually, the problem is not so easy as it looks.

The first practical method that appeared to us was to separate the liquid from the gas by means of some form of movable partition. The principle can be illustrated by a piston free to move in a cylinder, compressed gas being on one side of the piston and liquid on the other. If we open a valve at the liquid end it is quite clear that liquid will be ejected, regardless of the position of the cylinder, provided the gas pressure is great enough.

This arrangement as it stands is quite impracticable and it became necessary to find some kind of elastic partition, with no sliding movement, to replace the piston. Eventually we housed the liquid in a bag of very thin lead snugly fitting into its end of the cylinder. If pressure were now applied to the other end of the cylinder, or rather generated within it, the lead bag and its contents would obviously be put in a state of compression, and if the distal end of the bag were punctured, its contents would be free to escape through a suitably placed orifice in the cylinder end, the lead bag collapsing in step with the discharge.

It was our original intention to develop the pressure necessary for the discharge at the actual time that the machine came into operation, since we argued that if there was no permanent storage of pressure there could be no leakage, and we proposed to use as pressure generator a cartridge filled with some suitable slow burning mixture.

Here we met our first check. We had selected a composition whose rate of burning was remarkably slow and we had constructed a container which exactly accommodated the lead bag, the cartridge being disposed in a tube of smaller diameter screwed into the end of the main container. There was, as you will understand, no free space at all, and we supposed that the rate of discharge of the liquid would be approximately equal to the rate of generation of pressure by the cartridge, after that pressure has reached a certain value. We forgot, however, to make due allowance for the peculiarity of nature which ordains that the rate of combustion of such compositions as the one we were using is a function of the pressure, and nature reminded us of it, as usual with more force than discretion. Having completed the circuit which fired the cartridge we stood around watching with satisfaction the somewhat meagre trickle of liquid which almost immediately resulted. Suddenly there was a shattering report; the cylinder with its contents moved off in one direction with considerable speed, while the back-end-plate and the cartridge chamber, together weighing about ten or twelve pounds, steered, with appropriate irony, a direct course for the designer of the machine, myself, whose arm it broke before finally burying itself in a pile of empty tins.

We then decided that a fire extinguisher which was likely to blow up whenever it was brought into use was nearly as undesirable as one swinging like Foucault's pendulum, and we took steps to eliminate the possibility of danger.

We ascertained by experiment, carried out, I will almost unnecessarily add, with considerable circumspection, that the rate of burning of these compositions progressed along tolerably controllable lines until a critical pressure of about 100lbs. per square inch was reached. Above this pressure the curve became very steep; rapidly approaching the vertical condition which implies detonation.

We therefore increased the length of our main container so that only two-thirds of its volume were occupied by the lead bag, leaving one-third vacant space, and the amount of the composition we calculated so that if no increase of the vacant space occurred, the total amount of gas produced would be such that the resulting pressure would be less than the critical 100lbs. per square inch. It follows that if the lead bag is allowed to collapse normally, the pressure in the whole main container at the end of the collapse will be one-third of the total pressure possible in the original gas space, or about 30lbs. per square inch.

As a matter of fact, a series of gauge readings showed that the pressure increased regularly and fairly rapidly to about 30lbs. per square inch during the

initial stages of collapse and that this pressure was maintained practically constant until the last drop of liquid had been discharged, the pressure then rising a further two or three pounds as the last remnants of the cartridge burnt themselves out.

The method we used for perforating the lead bag was simplicity itself. The appropriate end-plate of the main container was dished with a concavity on its inner side, from the base of which stood up a sharpened piercer which was perforated and in direct communication with the discharge pipe. That end of the lead bag was flat, and therefore bridged the concavity. The first effect of the generation of pressure at the other end of the container was to cause this end of the lead bag to bulge into concavity where, of course, it punctured itself on the projecting piercer.

The apparatus as it then stood was satisfactory up to a point which appeared to be impassable. That point was that while 30lbs. per square inch was more than enough for a spray assisted by gravity, yet it was not enough to give a good spray against gravity, that is to say, if the machine in which the apparatus was housed lay on its back. We therefore abandoned our original idea of generating pressure at the moment of operation and decided in favour of a permanent pressure machine.

An additional argument for the change was that in a no-pressure machine there is no ready means of ascertaining its pressure-tightness against the pressure when it is provided, whereas in the constant-pressure machine the addition of a gauge enables one to see immediately by casual inspection if the machine is in working order or not.

The adoption of this change rendered necessary a modification in the method of piercing the lead bag and the apparatus as it now stands is shown in diagram (Fig. 1). The diagram is almost self-explanatory, air is pumped through

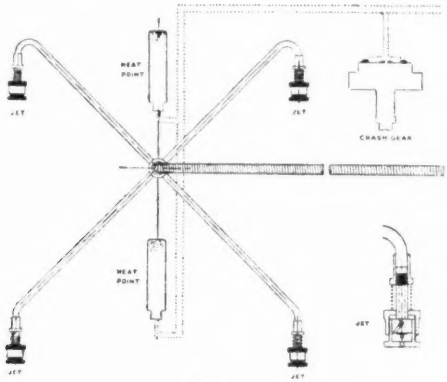


FIG. 1.

the Schrader valve until the gauge reads 100lbs. per square inch, when the apparatus is ready for action. The lead bag is modified so that one end is solid and has a centrally disposed diaphragm, which is pierced eventually by the spring-loaded piercer when that is released by the fracture of the electrically controlled detent.

I have dealt enough with the container except to point out one other result of the lead bag principle, and I will add that this result was taken into consideration when the design was first mooted. Since the propelling gas is entirely separate from the extinguishing liquid, there can be no solution of the gas in the liquid and, therefore, no breaking up of the jet due to this cause.

The liquid, then, is released by the fracture of a detent. The detent consists

of a small tube of metal in two halves, containing a few milligrammes of black powder and a miniature electrical primer. It is only necessary to pass a small current at any voltage over two through this primer to cause the black powder to explode and the tube to resolve itself into its component parts.

The next step is to consider how a circuit may be closed automatically in the event of a fire breaking out or in the event of a crash.

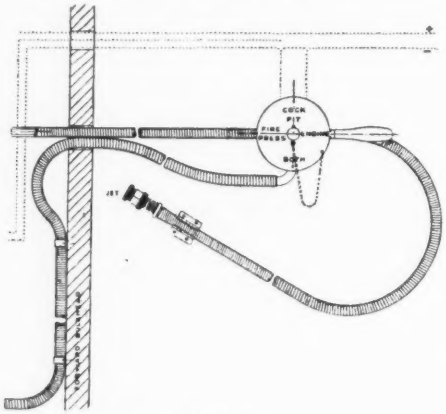


FIG. 2.

The first of these two problems is quite simple, but the manner in which we have solved it has one or two points of interest. Two strips of bi-metal are mounted by one end facing each other across a small block of fibre, and so turned that their free ends approach each other with rise of temperature. These free ends are bent over to form self-cleaning contacts.

This arrangement is quite efficient but prone to vibration. In order to prevent the possibility of contact being made by vibration or by accidental handling, a third strip of bi-metal is mounted at right angles to the other two and its free end provided with a small fibre distance piece, which normally lies between the ends of the two contacting strips. With rise of temperature this third strip bows backwards, until at the predetermined temperature it withdraws the distance piece and permits the contacting strips to approach one another. Thus the safety device is also temperature controlled.

The second problem, that of closing the circuit upon a crash, is not so easy as it seems. The apparatus must be so designed that it is adjustable within fairly wide limits, for the retardation it will experience in a crash depends largely upon its position in the machine. The Air Ministry require that the apparatus shall function in a plane which contains the plan of the aeroplane, but not at right angles to this plane. That is to say, it must function if the aeroplane crashes nose foremost, tail foremost, or wing-tip foremost, but not if it pancakes. They also require to be satisfied that the apparatus is adjustable and can be set, for example, not to function below, but to function above an impact equivalent to 5 G.

Our first apparatus consisted of a small and light aluminium casing in which a circular Staybrite slider was free to move in all directions in one plane, but which was normally held central by a spring-loaded stud which engaged with a concavity on its underside. Any retardation of its motion in the plane of operation will evidently tend to dislodge the slider from its central position and its resistance to such movement can be adjusted by varying the compression of the spring. A projecting point on its upper surface separates two contacts when the slider is in

its central position, but allows contact to be made when the central position is lost.

This design depends upon friction to too great an extent and it was modified in that a bronze ball took the place of the slider, this ball being held between a stationary stop and a spring-loaded cup. Upon the ball being dislodged, the spring-loaded cup travelled upwards through a distance equal to the diameter of the ball, and in so doing operated appropriate contacts.

This is quite satisfactory, but recently a further modification has suggested itself which dispenses with friction entirely. In this latest proposal the moving part consists of a globule of mercury which lies in a circular cavity, whose section through a diameter is a narrow ellipse. The surface-tension of the globule tends to keep it central, that is to say, in the widest part, but any impact on the edge of the elliptical cavity will cause the globule to travel more or less far into the narrowing portion towards the circumference. A central contact and a suitable annular contact are bridged by the mercury at a predetermined impact, and adjustment is obtained by varying the shorter axis of the ellipse. This would appear to be the farthest one can go towards simplicity though, perhaps, someone may come forward with an apparatus embodying no moving parts at all.

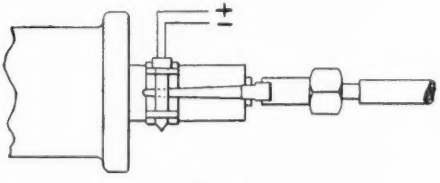


FIG. 3.

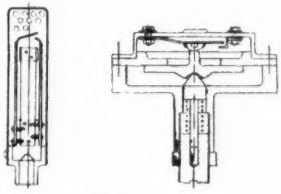


FIG. 4.

The rest of the layout as required by the Ministry need not occupy us. Manual operation is achieved by a push-button and some or all of the liquid can be diverted, if necessary, from the engine compartment to a flexible hand-pipe in the cockpit by means of a simple two-way valve.

While I use the word " simple " fairly frequently I really mean simple relative to the main problems; every detail, without exception, has presented its own minor problems in unexpected ways. It has been necessary to find a flexible tubing which will resist the action of this liquid, jets have had to be designed to suit its peculiarities, special methods of soldering have been evolved, special tools and plant laid down by the lead workers with which a thin-walled lead tube has been extruded of a greater diameter than was previously believed possible.

Before I leave this automatic equipment, there is another component, which while not called for by the Air Ministry is yet of more than passing interest. It was suggested that it might be an advantage to bring the extinguisher into action if the aeroplane on which it was carried adopted a dangerous angle and maintained that angle for more than a given time. The object is not to extinguish the fire which does not exist, but to cool down the hot parts of the engine so that the risk of fire is minimised when the machine crashes, as presumably it will. While this is of no practical use in fighting aircraft, which often maintain dangerous angles for quite considerable periods, yet it might be of use on passenger and freight-carrying craft which normally fly on an even keel.

The first suggestion which was put forward for this apparatus resembled an egg-timer. A sealed glass tube having a constriction at its middle contained at one end mercury, and at the other two contacts. It was supposed that if the tube were tilted to a cerain angle the mercury would flow down and bridge the contacts, the constriction providing the necessary time-lag.

A moment's consideration will reveal several disadvantages. First of all, it is limited to operation in one direction, and it is not amenable to accurate adjustment. But the disadvantage which definitely puts it out of court is that it will not work.

The point the inventor missed was that in an uncontrolled dive an aeroplane is generally accelerating, and if the engine is running it is possible that the acceleration would be, if not greater than G, at least very near G. But the downward tendency of the mercury is due to gravity alone and consequently the chances are that the mercury would never overtake the constriction.

In fact, what we must have is an apparatus sensitive to changes in its angular disposition, but insensitive to the forces of acceleration and retardation. Now this is quite a nice problem and one possible of solution, although a well-known firm of instrument makers once stated in no restrained language that it was a physical impossibility.

Let us assume that in our moving vehicle we have a rod mounted vertically and fixed at both ends. On this rod let us have a weight which is free to slide up and down the rod but which is attached to the upper end by a tension spring, whose strength is such that when the rod is vertical the weight hangs very nearly at the bottom of the system.

If we turn the rod through 90° gravitational pull on the weight is now

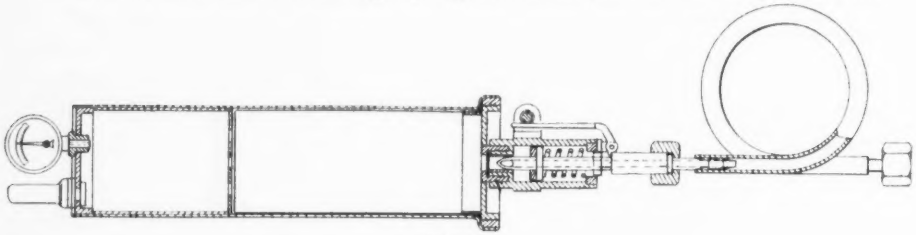


FIG. 5.

opposed by the rod and there is no component acting against the spring, so the spring will assert itself and draw the weight along the rod. For an intermediate angle the position of the weight on the rod will be proportional to the cosine of the angle of inclination.

Now constructionally, we have mounted the rod at right angles to the direction of movement of the vehicle. All forces due to acceleration and retardation act in the direction of movement and therefore can have no effect upon the movement of the weight, which is limited to a direction at right angles to the direction of movement of the vehicle. The only effect these forces have is to vary the friction between the weight and the rod.

This arrangement, modified slightly, of course, is perfectly satisfactory for the large angles with which we are concerned, but its application to motor cars, for example, for use as a clinometer, is restricted by the fact that for small angles such as are encountered by a motor car, the cosine varies very slowly.

All that is necessary now is to introduce a time-lag. At first sight it might seem that this could be done by damping down the movement of the weight by some suitable means, and I will leave you to decide why this is not feasible. Actually, we separate the two functions entirely, and use for our time-lag an electrically heated bi-metal strip, whose heating commences at the moment when the clinometer reaches the predetermined angle. In its actual form the rod is replaced by a glass tube about 2in. long, the weight by a bronze ball which rests upon a light compression spring. This bronze ball makes contact with an adjustable point at the upper end of the tube at the required angle, and undue

up-and-down vibration of the ball is reduced by filling the tube with a glycerine mixture.

By now you will have a fairly complete idea of the more recent developments in certain branches of fire extinguishing and you have probably come to the conclusion that it is all very childish. But you must remember that the subject is in its first infancy, it is only comparatively recently that anyone has realised that there were other methods of putting out a fire than by pouring large quantities of water over it. The drawbacks of water in large quantities are serious, it does enormous damage and its weight is often sufficient to cause the collapse of the building concerned. It is my belief that we are on the threshold of important discoveries in this direction; but I can give no more than the ghost of a suggestion as to what they may be.

We can accelerate combustion by catalysis, we can retard reactions by the same method, negative catalysis. Combustion is a function of chemical affinity, we can satisfy affinity in a variety of ways. The least offensive method of extinction is that of lowering the temperature to a point where combustion cannot continue. There are many unexplored ways of doing this. But until more is known of the mechanisms of catalysis, of affinity and of chemical behaviour generally we must concentrate on the materials which come most readily to hand, and I hope I have shown you that some attention is being paid to them. There is no reason why fire extinguishing should not take its place among the exact sciences.

THE CRITICAL DIAMETER OF THE CARBURETTOR CHOKE IN SUPERCHARGED ENGINES

BY

E. J. FEARN, M.Sc.(Eng.), A.F.R.Ae.S.

In a recent article* on supercharging, various practical conditions are given which place limits on the degree of supercharging possible with aero engines. Some time ago the writer was shown the results obtained with a supercharged engine and, although the performance was very creditable up to an altitude of 12,000 feet, above this altitude there was a remarkable decrease in power, this decrease being so considerable that it could not be readily accounted for. Various modifications were made in an attempt to improve the engine's performance at the higher altitudes, but without success, and it was only after a new type of carburettor had been fitted that improved results were obtained.

The following notes were made by the writer, and are of interest as they show that, if the engine is to develop ground level horse-power at altitudes, a certain minimum area is required at the carburettor choke.

Consider the "condition," that is, the pressure, density and absolute temperature of the induction air at two points in the carburettor system. Point (1) is taken at the inlet to the carburettor where the condition of the air is known at various altitudes, and point (2) is taken at the carburettor choke.

Now fundamentally,

$$\int_1^2 [dh + VdV/g + dp/\rho] = 0$$

where h = altitude in feet.
V = velocity—feet/sec.
p = pressure—lbs./sq. ft.
v = volume—cubic feet.
ρ = density—lbs./cubic foot.
T = absolute temp.—°C.
g = 32.2 ft./sec.^{2}
A_2 = area of choke tube—sq. ft.

The difference in height between the inlet and choke is negligible, *i.e.*, $dh = 0$.

$$\therefore \int_1^2 (VdV/g) = -\int_1^2 (dp/\rho) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

It is reasonable to assume that the compression in the choke be adiabatic since there is no appreciable transfer of heat to or from the walls of the carburettor at this point.

* "The Turbo-Compressor and the Supercharging of Aero Engines," by F/O. F. Whittle, A.R.Ae.S. (Journal of the Royal Aeronautical Society), November, 1931.

Hence taking pv^{γ}=constant.

$$\rho=\rho_1\,(p/p_1)^{1/\gamma} \qquad . \quad . \quad . \quad . \quad . \quad (2)$$

L.H.S. of equation (1)

$$=\int_1^2 V dV/g = V_2^{\,2}/2g$$

(since V_1 can be taken as zero, if point (1) be taken at a sufficient distance from the carburettor inlet).

R.H.S. of equation (1)

$$=-\int_1^2 dp/\rho = -(1/\rho_1)\int_1^2 (p_1/p)^{1/\gamma}\,dp$$

$$=-(p_1/\rho_1)^{1/\gamma}\,\{\,\gamma/(\gamma-1)\,\}\,\Big[p^{1-1/\gamma}\Big]_1^2 = \{\,-\gamma p_1^{\,1/\gamma}/\rho_1\,(\gamma-1)\,\}\,[p_2^{\,1-1/\gamma}-p_1^{\,1-1/\gamma}]$$

$$=\{\,\gamma p_1/\rho_1\,(\gamma-1)\,\}\,[1-(p_2/p_1)^{1-1/\gamma}]$$

Equating :—

$$V_2^{\,2}/2g=\{\,\gamma p_1/\rho_1\,(\gamma-1)\,\}\,[1-(p_2/p_1)^{(\gamma-1)/\gamma}] \quad . \quad . \quad . \quad (3)$$

$$V_2=\{\,[2g\gamma p_1/\rho_1\,(\gamma-1)]\,[1-(p_2/p_1)^{(\gamma-1)/\gamma}]\,\}^{\frac{1}{2}} \quad . \quad . \quad (4)$$

Now in order that the engine may develop a constant horse-power at all altitudes, the weight of air delivered to the engine (W lbs./sec., say), must be a constant quantity, and is equal to $A_2V_2\rho_2=A_2V_2\rho_1\,(p_2/p_1)^{1/\gamma}$.

$$\therefore\ W=A_2\rho_1\,(p_2/p_1)^{1/\gamma}\,\{\,[2g\gamma p_1/\rho_1\,(\gamma-1)]\,[1-(p_2/p_1)^{(\gamma-1/\gamma)}]\,\}^{\frac{1}{2}}$$

$$\therefore\ W=A_2\,\{\,[2g\gamma p_1\rho_1/(\gamma-1)]\,[(p_2/p_1)^{2/\gamma}-(p_2/p_1)^{(\gamma+1)/\gamma}]\,\}^{\frac{1}{2}}$$

Now for $(V_2\rho_2)$ to be a maximum and hence A_2 to be a minimum, we have :—

$$(d/dp_2)\,[(p_2/p_1)^{2/\gamma}-(p_2/p_1)^{(\gamma+1)/\gamma}]=0$$

$$\therefore\ (1/p_1)^{2/\gamma}\,(2/\gamma)\,(p_2)^{2/\gamma-1}-(1/p_1)^{(\gamma+1)/\gamma}\,\{\,(\gamma+1)/\gamma\,\}\,(p_2)^{1/\gamma}=0$$

$$\therefore\ p_2/p_1=\{\,2/(\gamma+1)\,\}^{\gamma/(\gamma-1)} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

For air, taking $\gamma=1.404$, $p_2/p_1=.528$.

Substitute for p_2/p_1 from equation 5 in equation 4 :—

$$\therefore\ V_2=\{\,[2g\gamma p_1/\rho_1\,(\gamma-1)]\,[1-2/(\gamma+1)]\,\}^{\frac{1}{2}}$$

$$\therefore\ V_2=\{\,2g\gamma p_1/\rho_1\,(\gamma+1)\,\}^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Re-writing equation (6) we have :—

$$V_2=\{\,[2g\gamma p_1/(\gamma+1)\,\rho_2]\,(p_2/p_1)^{1/\gamma}\,\}^{\frac{1}{2}}=\{\,[2g\gamma/(\gamma+1)]\,[(p_2)/\rho_2^{\,1/\gamma}]\,(p_1)^{(\gamma-1)/\gamma}\,\}^{\frac{1}{2}}$$

Substituting for p_1 from equation (5) :—

$$\therefore\ V_2=\{\,[2g\gamma/(\gamma+1)]\,[(p_2)^{1/\gamma}/\rho_2]\,p_2^{(\gamma-1)/\gamma}\,[(\gamma+1)/2]\,\}^{\frac{1}{2}}$$

$$\therefore\ V_2=\{\,g\gamma p_2/\rho_2\,\}^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Equation (7) gives the critical velocity of the air in the choke and is the velocity of sound in air at the same pressure and density.

Now $A_2=W/\rho_2V_2=W/\rho_1\,(p_2/p_1)^{1/\gamma}\,V_2$

Substitute for p_2/p_1 and V_2 from equations (5) and (6) respectively :—

$$\therefore\ A_2=W/\rho_1\,[2/(\gamma+1)]^{1/(\gamma-1)}\,[2g\gamma p_1/\rho_1\,(\gamma+1)]^{\frac{1}{2}}$$

$$\therefore\ A_2=W/\{\,g\gamma p_1\rho_1\,[2/(\gamma+1)^{(\gamma+1)/(\gamma-1)}]\,\}^{\frac{1}{2}} \quad . \quad . \quad . \quad (8)$$

Substitute our known values of g and γ in equation (8) :—

$$\therefore\ A_2=W/\{\,32.2\times1.404\,p_1\rho_1\,(2/2.404)^{2.404/1.404}\,\}^{\frac{1}{2}}$$

$$\therefore\ A_2=W/3.89\,[p_1\rho_1]^{\frac{1}{2}}$$

Let p and ρ be the ratios of the pressure and density at any particular altitude to the pressure and density at ground level.

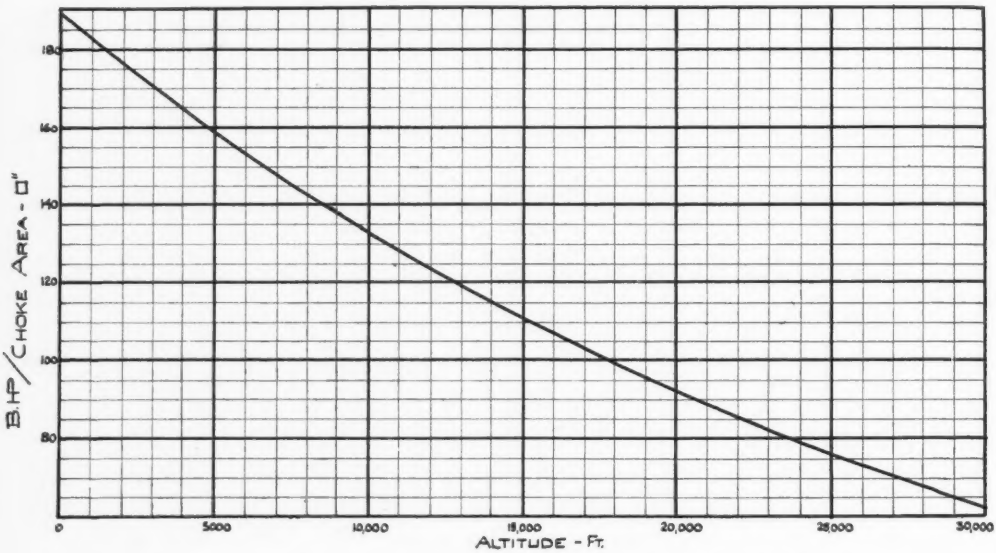
$$\therefore\ A_2=W/3.89\,[p\times14.68\times144\times\rho\times.076]^{\frac{1}{2}}=W/49.3\,[p\rho]^{\frac{1}{2}}$$

Assume that the air consumption be .11lbs. per b.h.p. per minute and let A_c ($=144\ A_2$) be the minimum choke area in square inches.

Then $W = (\text{b.h.p.} \times .11)/60$

and $A_c/144 = (\text{b.h.p.} \times .11)/(60 \times 49.3)\ [p\rho]^{\frac{1}{2}}$

$$\text{b.h.p.}/A_2 = 187\ [p\rho]^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (9)$$



From equation (9) a graph has been plotted giving the relation between b.h.p./A_2 and altitude. For example, a supercharged engine of 500 b.h.p., to operate successfully at an altitude of 25,000ft., requires the area of the carburettor choke to be $500/76.2 = 6.56$ sq. in. This represents the minimum area required, the velocity of the gas in the choke at this altitude then being equal to the velocity of sound in the gas at the same pressure and density.

Other conditions have also to be considered when determining choke areas, the most important being the suction head required for a given convergency or restriction. However, for the higher altitudes at which supercharged engines are operated, these conditions become of less importance and it is at these altitudes that the graph is of utility to prevent "throttling" due to an insufficient area at the choke.

CORRESPONDENCE

The Editor, THE JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY.

A NOTE ON THE SOLUTION OF DIFFERENCE EQUATIONS IN CERTAIN VIBRATION PROBLEMS

BY

CAPTAIN J. MORRIS, B.A., A.F.R.Ae.S.

In the January, 1932, number of the Journal I gave what appeared to be a simple solution of a determinantal equation which was a feature of Miss Chitty and Professor Southwell's R.38 Memorial Prize Essay, published in the December, 1931, issue of the Journal. Mr. T. W. K. Clarke, adopting an artifice similar to that used in my contribution, shows in a letter, published in the April, 1932, Journal, that the same solution can be arrived at directly from the difference equations, thus obviating the necessity for the evaluation of the determinant.

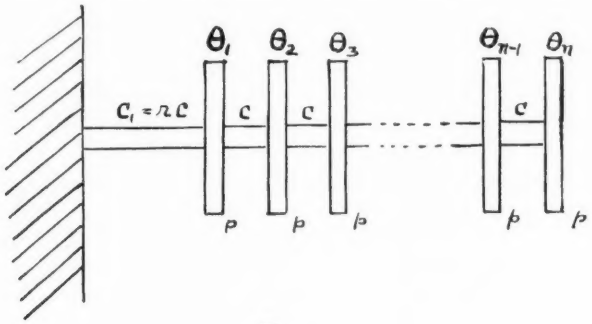


FIG. 1.

Furthermore, Mr. Clarke's method determines, incidentally, the relations between the amplitude constants which occur. I consider that Mr. Clarke's solution is very neat and a considerable improvement on the usual methods. I propose in this note to show how, with the adoption of Mr. Clarke's method, an appreciable simplification can be made in the solution of torsional vibration problems of importance in engine design. Take, for example, the case of n loads of equal moment of inertia on a shaft fixed at one end, the torsional stiffness of portions of shaft between consecutive loads being equal.

Referring to Fig. 1 in which p represents moment of inertia, c torsional

stiffness and the θ's angular displacements, we have for the equations of motion of the p's,

$$\begin{aligned}
p\ddot{\theta}_1 &= -rc\theta_1 + c(\theta_2 - \theta_1)\\
p\ddot{\theta}_2 &= -c(\theta_2 - \theta_1) + c(\theta_3 - \theta_2)\\
&\cdots\\
p\ddot{\theta}_{r-1} &= -c(\theta_{n-1} - \theta_{n-2}) + c(\theta_n - \theta_{n-1})\\
p\ddot{\theta}_n &= -c(\theta_n - \theta_{n-1})
\end{aligned}$$

If we assume as a solution that

$$\theta_1 = A_1 \cos(kt+\epsilon),\quad \theta_2 = A_2\cos(kt+\epsilon),\quad \ldots\quad \theta_n = A_n\cos(kt+\epsilon),$$

the A's, k and ϵ being constants, then on substitution we find that

$$\begin{aligned}
A_1[k^2 - (r+1)c/p] + A_2(c/p) &= 0\\
A_1(c/p) + A_2[k^2 - 2c/p] + A_3(c/p) &= 0\\
&\cdots\\
A_{n-2}(c/p) + A_{n-1}[k^2 - 2c/p] + A_n(c/p) &= 0\\
A_{n-1}(c/p) + A_n[k^2 - c/p] &= 0.
\end{aligned}$$

In the normal procedure the A's would be eliminated from these relations and this would result in a determinantal equation in k^2. But following Mr. Clarke, we notice that if

$$k^2 - 2c/p = -(2c/p)\cos\alpha$$

then all the above relations between the A's, except the first and last, will be satisfied by expressions for the A's of the form

$$A_s = A\cos(s\alpha+\beta)$$

where s is any number and A and β are arbitrary constants. This follows from the fact that

$$\cos(s\alpha+\beta) - 2\cos\alpha\cos(\overline{s+1}\alpha+\beta) + \cos(\overline{s+2}\alpha+\beta) = 0.$$

In order that the first and last difference equations should be satisfied by the same expression for the A's, the following relations between α and β must hold good, viz. :—

$$\begin{aligned}
\cos(\alpha+\beta)[(1-r) - 2\cos\alpha] + \cos(2\alpha+\beta) &= 0\\
\cos(n-1\alpha+\beta) + \cos(n\alpha+\beta)[1 - 2\cos\alpha] &= 0.
\end{aligned}$$

These may be written

$$\begin{aligned}
[(1-r)\cos\alpha - 1]\cos\beta - (1-r)\sin\alpha\sin\beta &= 0\\
\sin(n+\tfrac{1}{2})\alpha\cos\beta + \cos(n+\tfrac{1}{2})\alpha\sin\beta &= 0.
\end{aligned}$$

Eliminating β we find that α must satisfy the equation

$$\tan n\alpha \tan\alpha/2 = r/(2-r) \qquad (1)$$

and, further, that corresponding to any value of α obtained from this equation, the appropriate β is given by

$$\begin{aligned}
\tan\beta &= -\tan(n+\tfrac{1}{2})\alpha\\
\text{or } \beta &= \pi - (n+\tfrac{1}{2})\alpha
\end{aligned}$$

If we solve equation (1) for α we obtain the corresponding frequency $k/2\pi$, where

$$k^2 = (4c\sin^2\alpha/2)/p$$

Let $\alpha_1, \alpha_2, \alpha_3, \ldots \alpha_n$ be the values of α which satisfy equation (1) and let $k_1, k_2, k_3, \ldots k_n$ be the corresponding values of k, then

$$\begin{aligned}
\theta_1 &= A_1\cos(k_1t+\epsilon_1) + B_1\cos(k_2t+\epsilon_2) + \ldots + N_1\cos(k_nt+\epsilon_n)\\
\theta_2 &= A_2\cos(k_1t+\epsilon_1) + B_2\cos(k_2t+\epsilon_2) + \ldots + N_2\cos(k_nt+\epsilon_n)\\
&\cdots\\
\theta_n &= A_n\cos(k_1t+\epsilon_1) + B_n\cos(k_2t+\epsilon_2) + \ldots + N_n\cos(k_nt+\epsilon_n)
\end{aligned}$$

where

$$A_s = A \cos (s\alpha_1 + \beta_1)$$
$$B_s = B \cos (s\alpha_2 + \beta_2)$$
$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$
$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$
$$N_s = N \cos (s\alpha_n + \beta_n)$$

Now

$$\beta_r = \pi - (n + \tfrac{1}{2})\ \alpha$$

so that

$$\cos (s\alpha_r + \beta_r) = -\cos (n - s + \tfrac{1}{2})\ \alpha_r$$

There thus remain $2n$ constants, viz. :—A, B, C, . . . N; ϵ_1, ϵ_2, ϵ_3, . . . ϵ_n. These are determined from the initial values of the θ's and $\dot{\theta}$'s.

REVIEWS

Metallurgy

By Edwin Gregory, B.Sc., A.Met.F.I.C. (Blackie and Son, Ltd.) 17/6.

This is a book of a useful type which aims at the provision of an introduction to the study of metallurgy. It contains well written chapters on iron, steel, the constitution of metallic systems, special steels, stainless steels, and concludes with a discussion of various non-ferrous alloys, including copper alloys, duralumin and the recent R.R. alloys.

It is possible that many engineers will find that this work will contain as much on the subject of metallurgy as it is necessary for them to know, but for others it forms an excellent introduction to a more complete study of the subject.

It is well written and well illustrated and can be thoroughly recommended.

The Airplane and its Engine

Chatfield Taylor. 2nd edition. McGraw Hill Publishing Co., Ltd.

This is a text book of the type which aims at giving the reader as much instruction as possible without frightening him by the use of mathematical symbols. Such text books unquestionably perform useful work in imparting information to those who would never look at a more advanced work.

It deals with the aeroplane in a manner which should lead even the most ignorant to understand something about the subject and then proceeds to give a similar account of the aeroplane engine.

Being an American publication most of the numerous illustrations are naturally of American machines, but a few samples of Continental and British practice are included.

This is a well written book which should fulfil its purpose adequately and is specially suitable for those who, while being interested in aeronautics, have no technical training. They will find a large amount of information on all aeronautical matters well and clearly explained.